Aerobic Digestion of Organic Sludges Containing Inorganic Phosphorus Precipitates

Volume II

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The Scientific Liaison Officer for this project was
Dr. B.E. Jank, Fisheries and Environment Canada.

Enquiries pertaining to the Canada-Ontario Agreement RESEARCH
PROGRAM should be directed to -

Wastewater Technology Centre
Canada Centre for Inland Waters
Fisheries and Environment Canada
P.O. Box 5050
Burlington, Ontario   L7R 4A6

Ontario Ministry of Environment
Pollution Control Branch
135 St. Clair Avenue West
Toronto, Ontario   M4V 1P5

AEROBIC DIGESTION OF ORGANIC SLUDGES

CONTAINING INORGANIC PHOSPHORUS PRECIPITATES

VOLUME II

Sludges Precipitated by Lime Additions

to Raw Sewage

by

Dr. J. Ganczarczyk, P. Eng., Professor
and
Dr. M.F.D. Hamoda, P. Eng., Former Research Associate
Department of Civil Engineering
and
Institute for Environmental Studies
University of Toronto

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ABSTRACT

Lime treatment of raw sewage for phosphorus removal and/or for better clarification has been recently implemented in many wastewater treatment plants. However, aerobic digestion of the sludges that result from treatment has not yet been studied.

Laboratory experiments were carried out at $20^{\circ}C$ in completely mixed digestion units on sludges collected from a municipal wastewater treatment plant in Metropolitan Toronto. Tests were carried out simultaneously on lime-primary sludges (precipitated with $Ca(OH)_2$) and primary sludges (no chemical addition). Batch digestion experiments and semi-continuous (fed once a day) loading experiments were carried out. Lime-primary sludges from raw sewage precipitated with different lime dosages (140-600 mg/l) were studied at pH values in the range of 9-12. For comparative purposes, all sludges studied had initially a similar volatile solids content. Digester detention time was varied from 7 to 15 days to investigate the effect of this parameter on aerobic digestion of the sludges.

It was found that aerobic digestion of lime-primary sludges was feasible, but aeration periods of at least 15 days at $20^{\circ}C$ were required for effective treatment, especially for sludges having an initial pH in the higher range of values. The digestion process kinetics of lime-primary sludges with initial pH in the range of 9-10 were higher than those of the primary sludge (control) but for lime-primary sludges having initial pH in the range of 10-12, the high alkalinity or calcium content of the sludge resulted in lower process kinetics. The nitrification process was inhibited in digesters treating sludges precipitated with high lime dosages. The supernatant of the digested sludges had low soluble organic carbon and nutrient (phosphorus and nitrogen) contents. The aerobically digested lime-primary sludges had excellent dewatering characteristics.

RÉSUMÉ

De nombreuses usines d'épuration ont récemment adopté un traite-
ment d'addition de chaux aux eaux usées pour en éliminer le phosphore et
obtenir une meilleure clarification. Toutefois, on n'a pas encore étudié
la digestion aérobie des boues ainsi produites.

Des expériences effectuées en laboratoire à une température de
$20^{\circ}C$ se sont faites sur les boues complètement mélangées dans un digesteur.
Ces boues provenaient de la région urbaine de Toronto. Les expériences
ont porté à la fois sur des boues résultant du traitement primaire
à la chaux (précipitées avec du $CA(OH)_2$) et du traitement habituel
(sans agent chimique), ces dernières servant de témoin. On a procédé
à des essais de digestion par lots et de charge semi-continue (une par
jour). Les boues du traitement primaire dosées de 140 à 600 mg de chaux
par litre ont fait l'objet d'observations à des pH variant entre 9 et 12.
Aux fins de comparaison, toute les boues étudiées avaient le même teneur
initiale en matières volatiles. Le stage dans le digesteur a duré de
7 à 15 jours pour évaluer d'incidence de ce paramètre sur la digestion
aérobie des boues.

On a observé que la digestion aérobie était possible après un
traitement primaire à la chaux, mais qu'il lui faillait une oxygénation
d'au moins 15 jours, à $20^{\circ}C$, pour être efficace, plus particulièrement
si le pH initial était élevé. La digestion des boues de chaux dont le
pH initial se situait entre 9 et 10 a été plus rapide que celle des
boues témoins; toutefois, la basicité ou la teneur élevée en calcium
des boues dont le pH initial se situait entre 10 et 12 a ralenti le
processus. La nitrification a été nulle dans les boues qui avaient
précipité dans le digesteur sous l'action de fortes doses de chaux.
La liqueur superficielle des boues digérées avait une faible teneur en
carbone organique soluble et en éléments nutritifs (phosphore et azote).
Les boues obtenues par digestion aérobie se déshydrataient très
facilement.

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CONCLUSIONS

1. Aerobic digestion of lime-primary sludges proved feasible even for sludges with initial pH as high as 12.

2. In both the batch and semicontinuous loading experiments the pH of the lime-primary sludges decreased from an initial value in the range 9 - 12 to an average value of 8.5 and remained constant at this level during aerobic digestion regardless of digestion time. The pH of the primary sludge fluctuated during aerobic digestion.

3. The total alkalinity of the lime-primary sludge did not decrease as a result of aerobic digestion and was different for different lime-primary sludges. In contrast, the total alkalinity of the primary sludge showed a substantial decrease during aerobic treatment as a result of nitrification. The digestion time of the primary sludge had a great effect on the alkalinity changes.

4. Lime-primary sludges having initial pH in the moderate range of 9 - 10 showed a higher degree of organic solids decomposition than primary sludges, since the former apparently contain some fractions of organic material of lower molecular weight precipitated from sewage. However, lime-primary sludges having higher initial pH showed a lower degree of organic solids decomposition. For all sludges studied, the organic solids decomposition was a function of digestion time. The rate of decrease of the sludge organic solids decreased as the digestion period increased.

5. The kinetics of organic solids decomposition was affected by the alkalinity, or calcium ion contents, during aerobic digestion of lime-primary sludges. A good linear correlation was found between the decomposition rate constant (k) based on volatile suspended solids reduction and the total alkalinity. The rate constant increased as alkalinity decreased.

6. The oxygen uptake rate of the sludges normally decreased with increasing digestion time. Batch digesters produced sludges that generally had lower oxygen uptake rates than those treated in semi-continuous loading digesters.

7. The nitrification process which usually accompanies aerobic digestion of sludges was inhibited in digesters treating lime-primary sludges precipitated with high lime dosages.

8. Release of mineral nutrients (phosphorus and nitrogen) and organic carbon during the aerobic digestion of primary sludges or lime-primary sludges was negligible and supernatant from the digested sludges had a low nutrient content.

9. Aerobically digested lime-primary sludges had excellent dewatering characteristics and produced relatively clear supernatant as compared to primary sludges.

10. Detention periods of at least 15 days were required in the semi-continuous loading experiments treating lime-primary sludges at $20^{o}C$, especially when sludges having initial pH values in the higher range were treated.

RECOMMENDATIONS

1. It is recommended that this study be continued on a pilot plant scale for sludges precipitated with relatively small dosages of lime (initial pH in the range of 9 - 10). This pilot plant study should be followed by a preliminary engineering and costs estimation. It appears that a wastewater treatment method composed of lime precipitation and aerobic digestion of resulting sludges may be economical in some circumstances.

2. Several additional studies seem desirable in the field of aerobic digestion of organic sludges. These are:

   a) studies on two-stage digestion with a partial dewatering of sludges after first stage of treatment;

   b) studies on aerobic digestion of highly concentrated sludges;

   c) studies on aeration and mixing in relatively dense systems of concentrated sludges; and,

   d) studies on application of elutriation to improve dewaterability of aerobically digested sludges, etc.

1.   INTRODUCTION

The lime precipitation process for raw sewage treatment may be used effectively for an improvement of primary clarifier operation, to remove phosphorus from wastewater or to prepare wastewater for treatment by activated carbon (Buzzel and Sawyer, 1967; Black and Lewandowski, 1969; Albertson and Sherwood, 1969; Schmid and McKinney, 1969; Spohr and Talts, 1970; and Zuckerman and Molof, 1970).

There is a general relationship between lime addition for particular wastewaters and the pH of the resulting wastewater. The specific dosages of lime depend on wastewater hardness, alkalinity, suspended solids concentration and orthophosphate content (ibid).

1.1   Lime Sludge Formation

The quantity of sludge precipitated from sewage by lime addition is larger than the amount of primary sludge obtained without the addition of lime because of increased removal of suspended solids, coagulation of some colloids, and the formation of calcium phosphate, calcium carbonate and magnesium hydroxide precipitates. In general, the quantity of solids increases by a factor of two to five.

1.2   Treatment of Lime-Precipitated Sludges

The sludges formed by the lime treatment of sewage generally show a good ability to thicken. The sewage hardness and alkalinity may have an important influence on this operation (Black and Lewandowski, 1969). It is possible that the initial increase in the pH of the sludge and/or the adsorption of a small amount of the chemical solids onto the raw sludge particles at lower lime addition levels results in a deterioration of the physical characteristics of the sludge. At higher lime dosages, as the production of chemical solids increases, sludge might thicken more readily (Minton and Carlson, 1973).

Incineration and recalcification of lime-precipitated sludges are presently being studied. The first process is not very effective, and the economy of the latter, which is usually associated with the preliminary concentration of the sludge by centrifuging, depends mostly on the local conditions.

During anaerobic digestion of lime-precipitated sludges operational problems are frequently encountered. Aerobic digestion of lime-precipitated sludges was not, to our knowledge, studied prior to this work.

1.3 Objectives

This study, which constitutes Phase II of the research, is a continuation of the work carried out in 1972-73 (Ganczarczyk and Hamoda, 1973). The main aims of Phase II were to obtain information on:

1) the feasibility of the aerobic digestion of sludges resulting from lime precipitation of raw sewage; and

2) the performance of aerobic digesters used in the treatment of these sludges under batch and semicontinuous loading conditions.

These objectives were met by investigating the process in five series of experiments as follows:

a) preliminary batch studies for sludges precipitated by lime of different dosages for a general determination of the behaviour of lime sludges during aerobic digestion (Series 1);

b) detailed batch studies for sludges precipitated at lime addition rates selected in Series I experiments; in this series an extensive analytical program was followed (Series II);

c) semicontinuous loading digestion studies on sludges having different initial pH values (sludges precipitated by different lime dosages). Three series of experiments (Series III, IV and V) were carried out. Each series was designed to study lime-primary sludges at a particular range of initial pH values in three digesters operated at different hydraulic residence times. The lime-primary sludges studied had initial pH values in the range 9.5 - 10.0, 10.5 - 11.0, and 11.5 - 12.0 for Series III, IV and V, respectively.

A control digester treating primary sludge with no chemical addition was operated for each series of experiments.

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2. EXPERIMENTAL DETAILS

2.1 Experimental Program

Five consecutive series of laboratory experiments were carried out. Series I and II were batch tests each lasting for 28 days. Series III, IV and V were semicontinuous tests, each conducted for one month following 10 days of acclimation. All experiments were conducted at 20°C in a constant temperature room. Table 1 summarizes the scheme of experimentation followed in this study.

In these experiments, hydraulic residence time was the variable parameter. The hydraulic residence time was identical with the time of aeration in the batch experiments and the detention time based on liquid sludge displacement in the semicontinuous experiments. The solids residence time (SRT), also called the sludge age, is equal to the hydraulic residence time in the digesters as operated in these experiments.

2.2 Material

All sludge samples used in these experiments were obtained from the Humber Pollution Control Plant in Metropolitan Toronto. In both Series I and II of the experiments, three samples each of 250 litres were collected from the wastewater distribution channel before the primary settling tank. The distribution channel received raw wastewater after screening and grit removal. Different dosages of lime were added to these samples. Technical grade hydrated lime, $Ca(OH)_2$, was used for chemical precipitation. The lime dosages used were 200, 400 and 600 mg/l. Immediately after the addition of lime dosage to each sample in large cylindrical containers, rapid mixing was applied for three minutes using a variable-speed, motor-driven, paddle stirrer. This was followed by 30 minutes of gentle mixing after which samples were left to settle for approximately one hour and sludges were collected. The control primary sludge sample was collected from the sludge wasting line of the primary clarifier; the theoretical detention time in the clarifier was two hours. A similar procedure was used in the Series III, IV and V experiments except that 180 litres of wastewater were collected twice a week during this semicontinuous

TABLE 1. SCHEME OF THE EXPERIMENTS

Experiment Series	Digester Loading Procedure	Description of Sludge Used	Detention Time in Digester	Period of Digester Operation
I	Batch (initial feed only at zero time)	Primary (control) Sludge: Sludge A Lime-primary sludges: Sludge B (precipitation by 200 mg/l lime, initial pH = 9.86) : Sludge C (precipitation by 400 mg/l lime, initial pH = 11.30) : Sludge D (precipitation by 600 mg/l lime, initial pH = 11.85) : Sludge E (precipitation by 600 mg/l lime, pH initially adjusted at 7.40)	Aeration for 28 days	28 days
II	Batch (initial feed only at zero time)	Primary (control) Sludge: Sludge A Lime-primary sludges: Sludge B (as in Series I, but pH = 10.24) : Sludge C (as in Series I, but pH = 11.45) : Sludge D (as in Series I, but pH = 11.90)	Aeration for 28 days	28 days
III	Semicontinuous (once-a-day feed)	Primary (control) Sludge: Digester A Lime-primary sludge: Digesters B, C and D (initial pH range 9.5 - 10.0, precipitation by 140 - 200 mg/l of lime)	Digester A: 15 days Digester B: 7 days Digester C: 10 days Digester D: 15 days	30 days (after 10 days of acclimation)
IV	Semicontinuous (once-a-day feed)	Primary (control) Sludge: Digester A Lime-primary sludge: Digesters B, C and D (initial pH range 10.5 - 11.0, precipitation by 300 - 350 mg/l of lime)	Digester A: 10 days Digesters B, C and D as in Series III	32 days (after 10 days of acclimation)
V	Semicontinuous (once-a-day feed)	Primary (control) Sludge: Digester A Lime-primary sludge: Digesters B, C and D (initial pH range of 11.5 - 12.0, precipitation by 600 - 650 mg/l of lime)	Digester A: 10 days Digesters B, C and D: as in Series III	29 days (in continuation of Series IV)

loading period. In each case, lime dosages were calculated based on the alkalinity of wastewater collected in order to obtain lime sludges of pH in the ranges of 9.5 - 10, 10.5 - 11, 11.5 - 12 for the Series III, IV and V experiments, respectively. Control primary sludge was collected in each case in a similar manner as in Series I and II.

Before being used in the experiments, sludge samples were passed through No. 10 mesh screens to obtain a homogeneous sludge feed. In Series III, IV and V, the solids content of sludge samples was adjusted, immediately after collection, either by a thickening procedure or by dilution using raw sewage in the case of control primary sludge and lime treated effluent in the case of lime sludge.

In Series III, IV and V, both lime and control primary sludges that were collected twice a week for the daily feed of the digesters, were stored in 3-litre Erlenmeyer flasks, and kept refrigerated at $4^{o}C$ for a maximum period of four days.

2.3   Experimental Set-Up

Bench-scale, completely-mixed digesters were employed in these experiments. Each digester had a capacity of $3\frac{1}{2}$ gallons and consisted of an 8-3/4 inch diameter by 18 inch high pyrex jar. In order to meet process air requirements and partially provide sludge mass mixing, compressed air was passed through a circular tygon tube ring having fine perforations. The aeration ring rested on the bottom of the digester. Complete mixing conditions were maintained in each digester by employing a laboratory, motor-driven, variable speed stirrer with two inch diameter propellers mounted centrally. To minimize evaporation losses, each digester was covered with a circular one inch thick, plexiglass plate with three openings for service connections, one of which was provided for the escape of exhaust gases. Provisions were made in the cover plate at its contact with the pyrex jar to insure an air seal for the digester when necessary. The sealed digester system was only used for ammonia stripping experiments.

Glass and rubber tubes were used to connect the perforated tygon tube ring to the laboratory compressed air-line. The air flow to the digesters was controlled by air flow control valves and the air

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flow rate to each digester was measured by an air flow meter. Air was supplied to each digester at a rate of about 1.0 litre/min/litre of liquid sludge volume. The air was saturated with distilled water and freed from any greasy impurities before being supplied to the units. Pertinent features of the experimental set-up are illustrated in Figure 1.

2.4   Operating Procedures

Before withdrawing digested sludge samples from the experimental digesters, ammonia-free distilled water was added as necessary to make up for any liquid volume losses resulting from evaporation. Solids which had accumulated on the inside walls of digesters were resuspended. The digested sludge was withdrawn from each digester by siphoning to a 500-ml Erlenmeyer flask through a $\frac{1}{4}$-inch diameter glass tube. Sludge volumes were measured using graduated cylinders.

The dissolved oxygen concentration in digesters was monitored frequently during operation and was often more than 4 mg/l since sufficient air was supplied to all digesters. Foaming was often experienced in the earlier period of digester operation. However, as the system stabilized, the foaming problem gradually disappeared.

The motor-driven laboratory stirrers used for mixing the sludge mass in the digesters were operated at a sufficient speed to maintain adequate mixing.

2.4.1   Batch loading experiments (Series I and II)

The batch digestion experiments were carried out using 13 litres of sludge in each laboratory digester. In Series I, five sludges, namely A, B, C, D and E were used, corresponding to the primary (control) sludge and the lime-primary sludges that were precipitated with lime dosages of 200 mg/l, 400 mg/l, 600 mg/l and 600 mg/l (with initial pH adjustment), respectively. In Series II, sludges similar to A, B, C and D of Series I were used but in this case, because of the alkalinity of the raw sewage used, the lime-primary sludges, B C and D had initial pH values that were different than those of sludges B, C and D in Series I. The alkalinity of the raw sewage used in Series I and II were 210 mg/l and 126 mg/l as $CaCO_3$, respectively. Aeration of sludges continued for 28 days. Digested sludge samples were withdrawn from the digesters
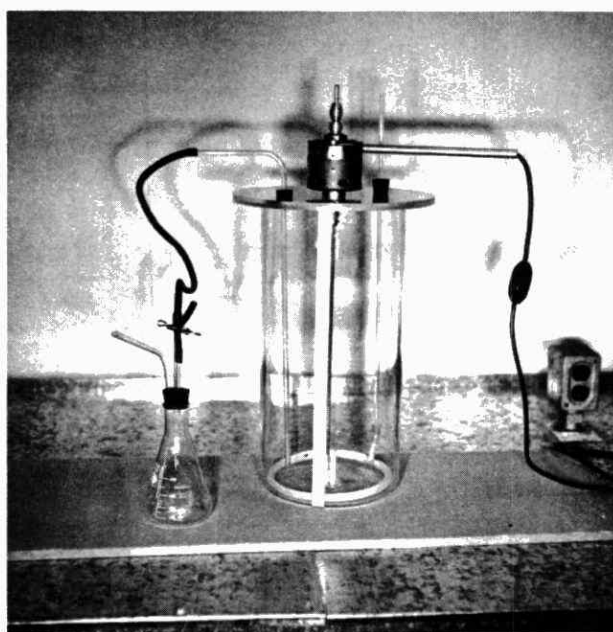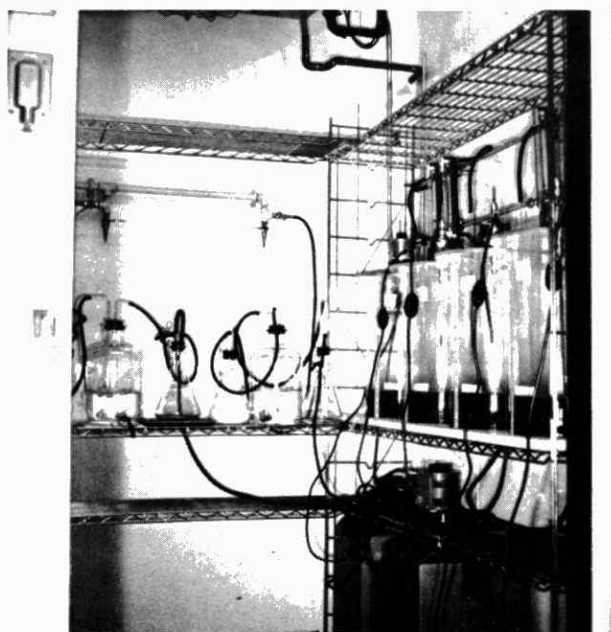
FIGURE 1.   EXPERIMENTAL SET-UP

for analyses according to a preset sampling schedule. More extensive analytical control was conducted during Series II than during Series I of the experiments since the latter series of experiments, as first intended, were undertaken to provide preliminary knowledge on the feasibility of the aerobic digestion of lime-primary sludges.

2.4.2 Semicontinuous loading experiments (Series III, IV and V)

The operating sludge liquid volume in each of the four digesters fed once a day was maintained at 3.5 litres throughout the study period. One digester (A) received primary sludge (control) while the other three digesters (B, C and D) were fed lime-primary sludges.

At the beginning of each of the Series III and IV experiments, initial charges of 3.5 litres of each of the sludges to be studied were aerated continuously for 10 days. The purpose of this initial batch digestion was to acclimate the sludge microbial population to the existing environment. Directly after the 10 day batch acclimation, the semicontinuous loading of digesters was started. Series V of the semicontinuous loading experiments was initiated as a continuation of the Series IV experiments and no initial batch acclimation was necessary. Each semicontinuous loading series of experiments lasted for 29-32 consecutive days.

The feed sludges were collected twice a week. Efforts were made to minimize the variations in the feed sludge concentration by adjusting its solids content using a dilution or thickening procedure as previously discussed. Although this procedure did not provide a constant initial feed solids concentration, it did minimize variation. Achievement of a constant solids concentration would have required a control procedure that would have delayed the preparation of the feed.

Feed sludges were stored in the refrigerator at $4^{\circ}C$ for a maximum of four days. Sludges refrigerated for this period showed essentially no change in COD and volatile solids content. However, a maximum drop in pH of one unit was reported for feed lime sludges after four days of refrigeration. The refrigerated feed sludges were allowed to warm up gradually to about $20^{\circ}C$ before being fed to the digesters.

In these experiments, for practical applicability, the feed lime-primary sludges were characterized by their initial pH rather

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than by the amount of lime used for precipitating the sludges. The pH of the feed lime-primary sludge was controlled in order to ensure a stable pH of the sludge feed to the digesters. The control was achieved by using lime dosages for sludge precipitation according to the alkalinity of the original wastewater.

The feed lime-primary sludges had initial pH values that were different for different series of the semicontinuous loading experiments. Lime-primary sludges having pH values in the ranges 9.5 - 10.0, 10.5 - 11.0, and 11.5 - 12.0 were used in Series III, IV and V, respectively. The lime dosages used for sludge precipitation were 140 - 200 mg/l to obtain a sludge pH of 9.5 - 10.0, 300 - 350 mg/l to obtain a sludge pH of 10.5 - 11.0, and 600 - 650 mg/l to obtain a sludge pH of 11.5 - 12.0.

Each day, at a fixed time, a predetermined volume of sludge feed was added to each digester immediately after the withdrawal of an equal volume of the digested sludge from the digester. In this way the hydraulic residence time in each digester was controlled. The hydraulic residence time in digester B was seven days; in digester C, 10 days and in digester D, 15 days for Series III, IV and V. The hydraulic residence time in digester A (control) was 15 days for Series III and 10 days for both Series IV and V. The daily withdrawal of digested sludge volumes and the addition of equal volumes of sludge feed in the amounts of 500, 350 and 235 ml was necessary to obtain theoretical hydraulic residence times of 7, 10 and 15 days, respectively, while maintaining a constant sludge volume of 3.5 litres in each digester.

2.5   Analytical Procedures

Analyses were performed on both the feed and the digested sludges. The analyses performed were total solids, total volatile solids, suspended solids, volatile suspended solids, chemical oxygen demand, oxygen uptake rate, pH, total alkalinity, ammonia nitrogen, nitrate nitrogen, total kjeldahl nitrogen, total phosphorus, total organic carbon, settle-ability test and filterability test. For determination of soluble materials, the supernatant was obtained by centrifuging sludge samples for 10 minutes at 1,500 rpm in a laboratory centrifuge; the supernatant was filtered through 0.45μ membranes, and measurements of soluble materials were made on the filtrate.

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Analytical methods used were the same as described in the previous report (Ganczarczyk and Hamoda, 1973). In addition, standard analytical procedures (APHA, Standard Methods, 1971) were followed in the measurements of chemical oxygen demand using the dichromate reflux method and in the determination of total alkalinity by titration with 0.02 N sulphuric acid solution.

3.   RESULTS AND DISCUSSION

3.1   Chemical Neutralization During Digestion

The changes in the pH of the sludges during batch digestion experiments (Series I and II) are shown in Figures 2 and 3. The pH of the lime-primary sludges B, C and D decreased substantially during the first three days of aeration, after which the pH of the sludges remained almost stable as aeration progressed. The pH of these sludges reached stable values that were essentially equal and independent of the initial pH of the sludge. The lime-primary sludge E whose pH was initially adjusted to 7.4 (Series I) showed an initial slight increase in the first three days of aeration, followed by a stabilization in pH as aeration progressed. The stability of the pH of the lime-primary sludges at prolonged periods of aeration indicated good buffering capacity of the sludge digestion system.

The changes in the pH of the primary (control) sludges A in Series I and II followed a different pattern from that of the lime-primary sludges. The pH of the sludge A showed a slight increase in the early stages of digestion followed by fluctuations with prolonged aeration probably due to the occurrence of nitrification.

Figures 4 to 6 show the daily changes in pH with the period of operation for the semicontinuous loading experiments (Series III, IV and V). The lime-primary sludges studied in each series showed similar patterns of pH changes characterized by a fairly constant sludge pH in digesters which were at steady state conditions.

At steady state, equal pH values were reported for lime-primary sludges in digesters operated at different detention times (digesters B, C and D). Moreover, the digested lime-primary sludges in Series III, IV and V experiments had similar pH values regardless of their original pH values prior to digestion. These results are in good agreement with those obtained from the batch loading experiments. They also indicate the good buffering capacity of the aerobic digestion system treating lime-primary sludges that can resist the pH changes which usually accompany the progress of aerobic digestion.
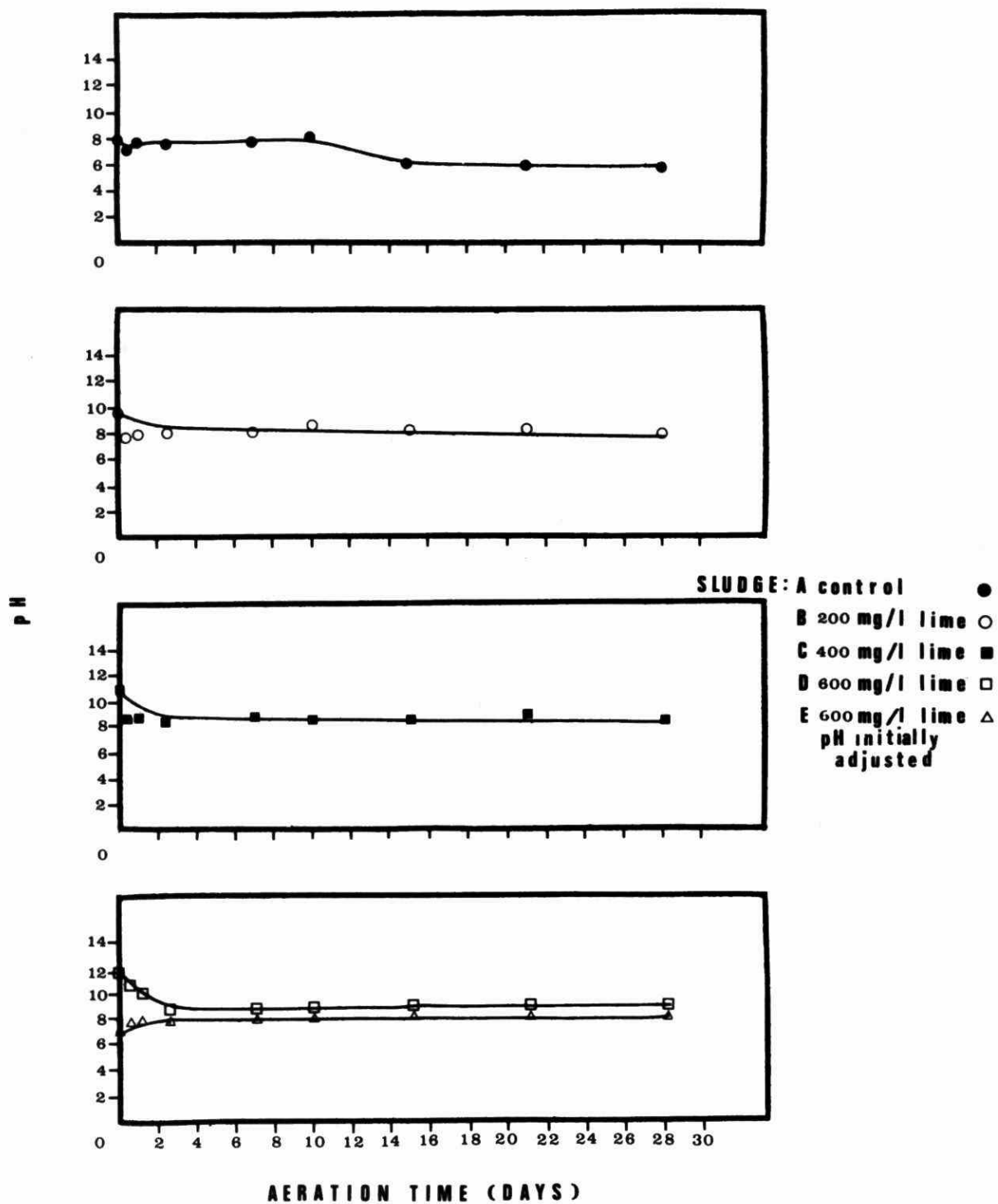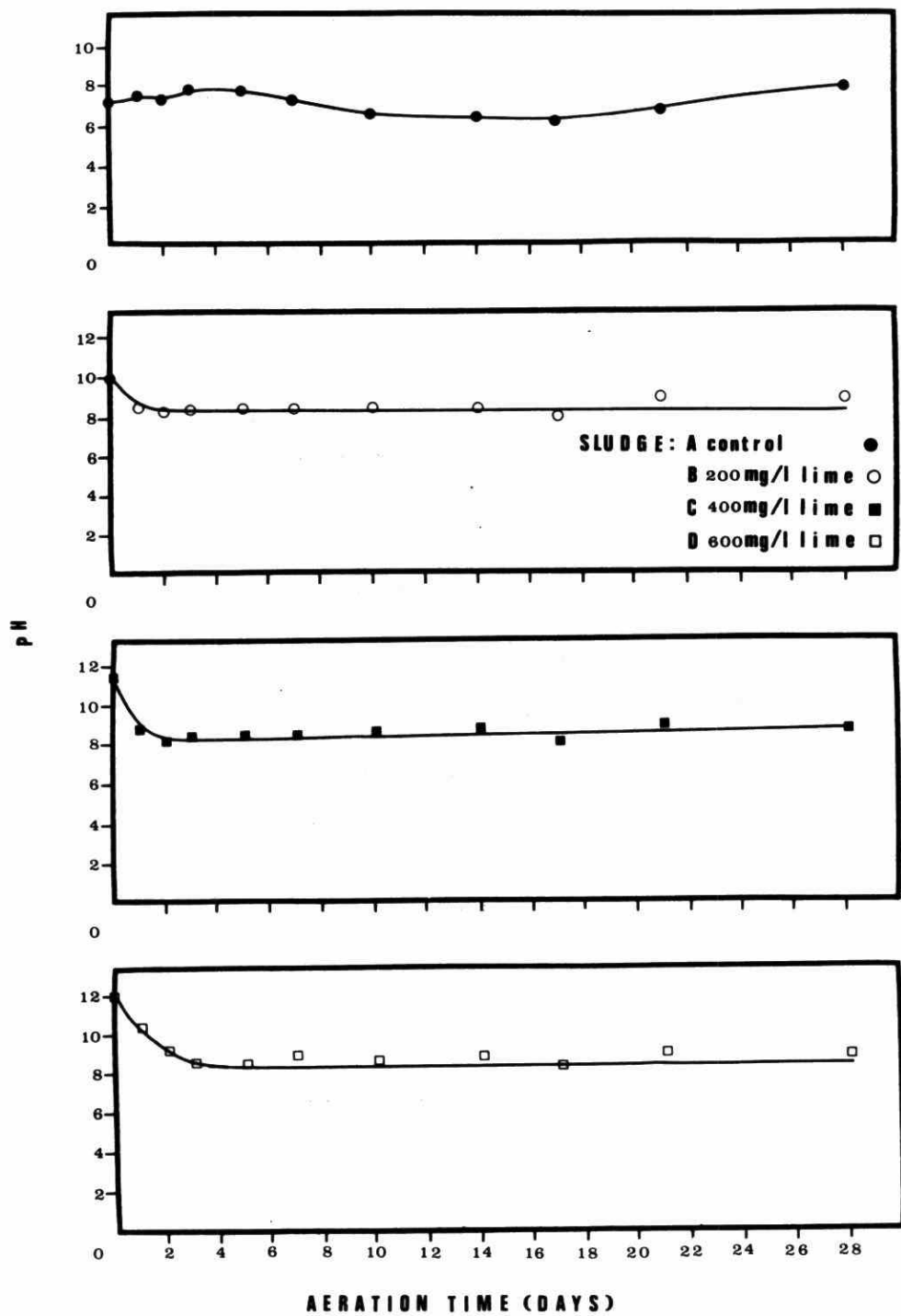
FIGURE 2. CHANGES IN pH (SERIES I)

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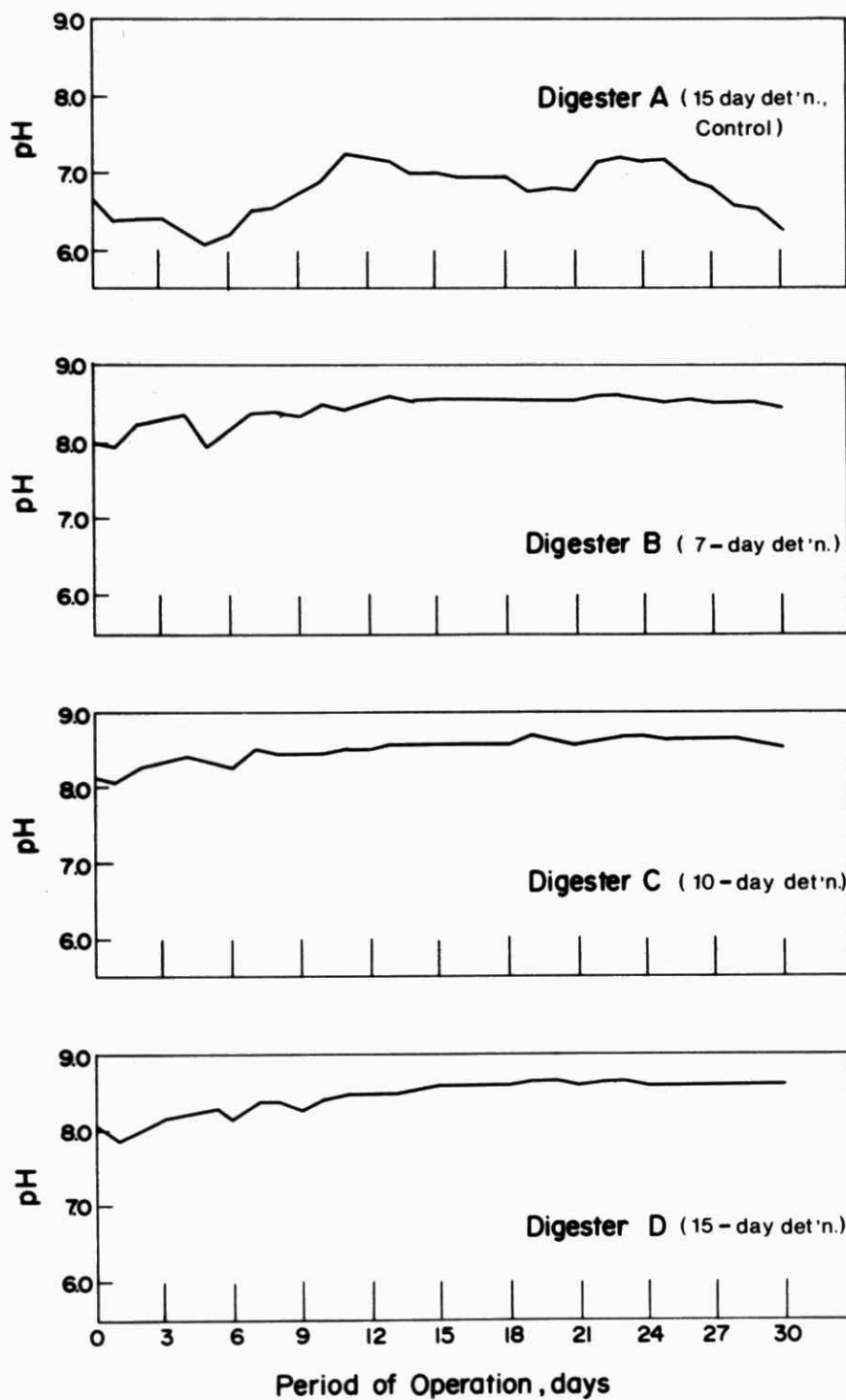FIGURE 3.   CHANGES IN pH (SERIES II)

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FIGURE 4.   DIGESTER OPERATING DATA — CHANGES IN pH   (SERIES III)
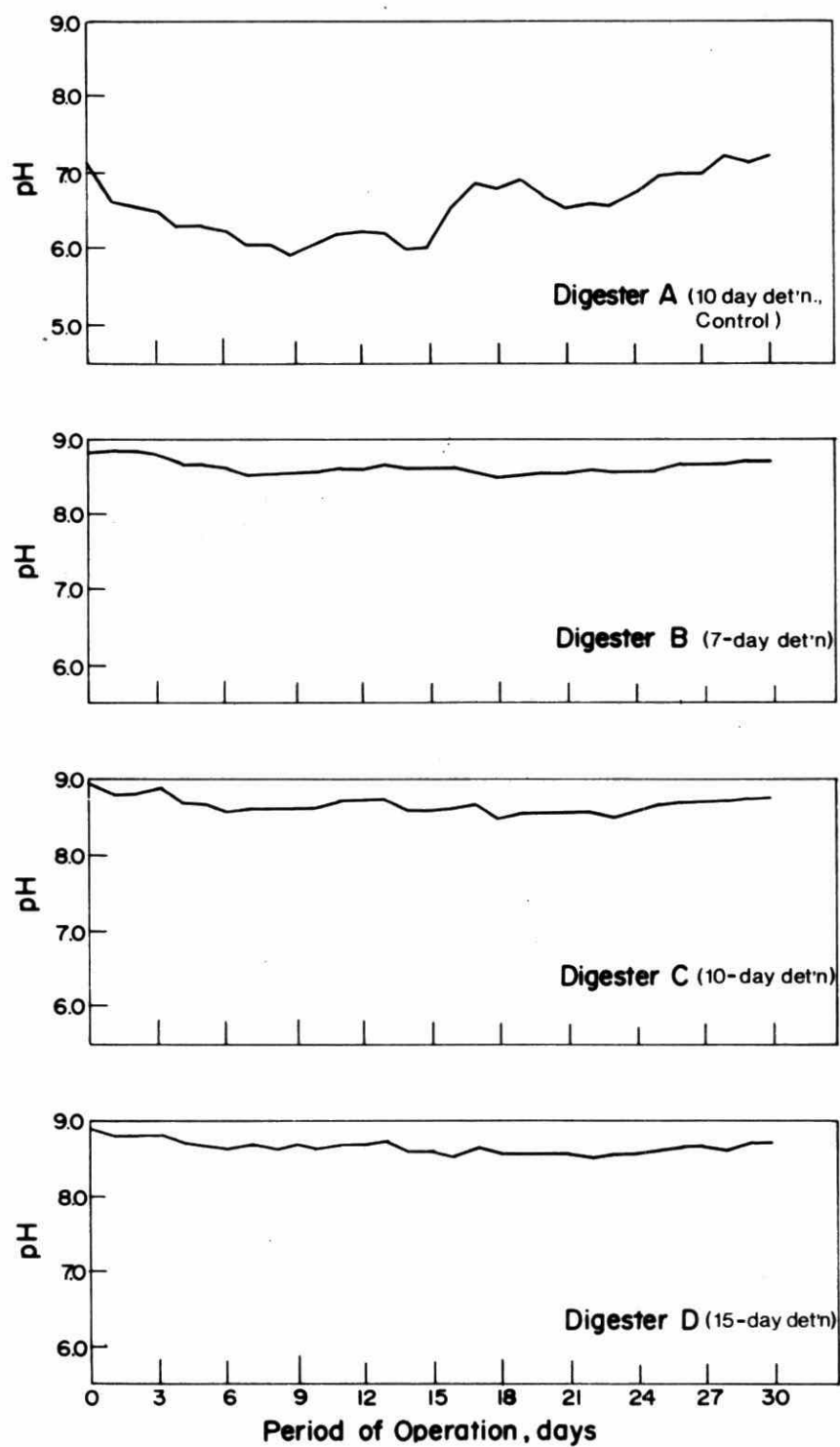
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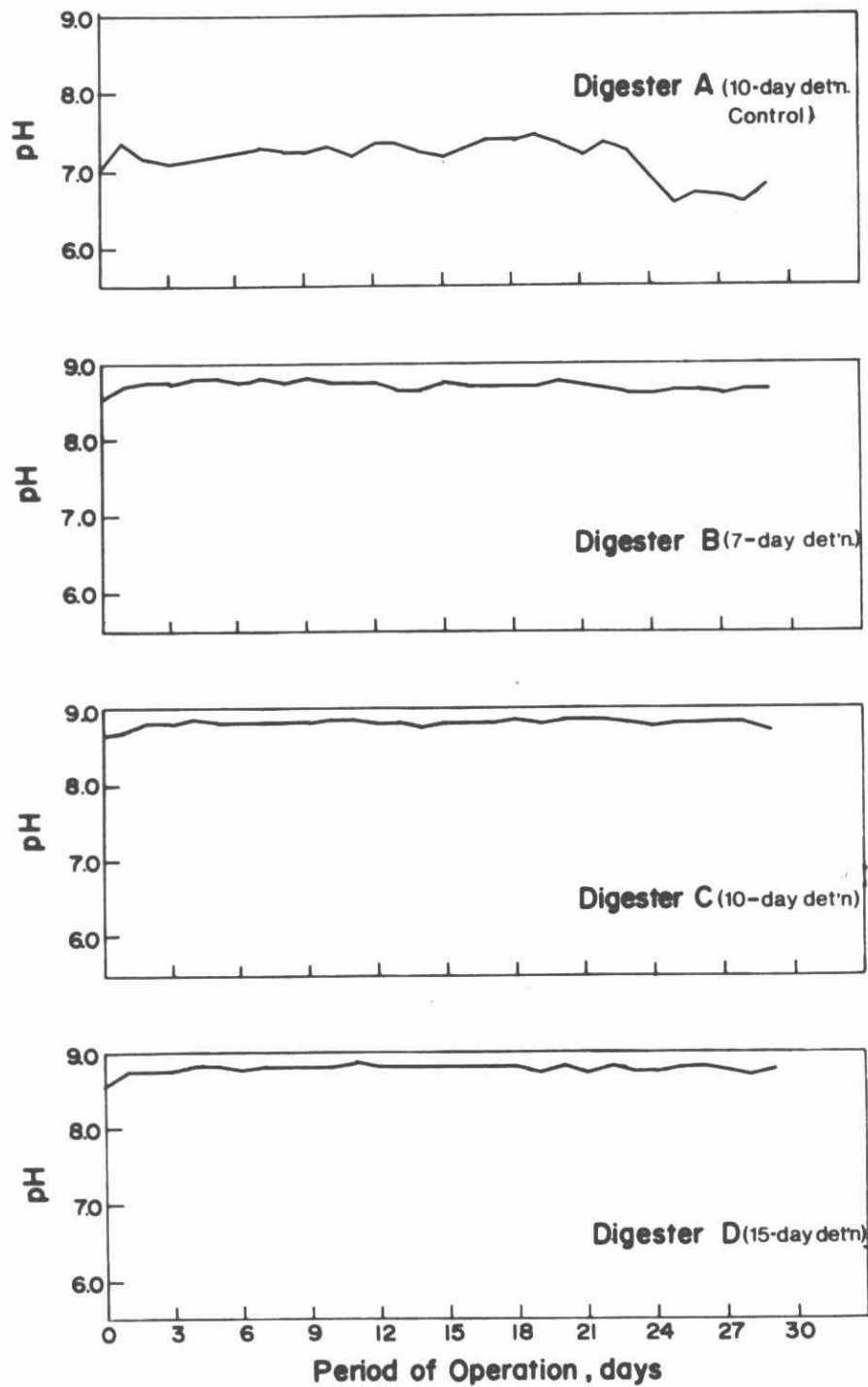FIGURE 5. DIGESTER OPERATING DATA – CHANGES IN pH (SERIES IV)

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FIGURE 6.   DIGESTER OPERATING DATA – CHANGES IN pH (SERIES $\mathbb{V}$)

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Fluctuations in pH values were recorded for digesters treating the primary (control) sludge A in Series III, IV and V even though the digesters were at steady state. A possible explanation is that the low alkalinity of the sludge in the digester makes the sludge less resistant to changes in pH during digestion. Such changes in pH are due to CO_2 production and the release of ammonia which may be further oxidized to nitrites and nitrates.

The changes in the total alkalinity during batch digestion (Series I and II) are shown in Figures 7 and 8. Figure 8 shows that alkalinity fluctuated considerably, increasing until a maximum value was reached within five to seven days and then decreasing until an equilibrium condition was attained. Since the alkalinity was not measured during the first seven days of the Series I experiments (Figure 7), only an educated guess can be made. However, the general pattern was similar to that observed in Series II in that there was an initial increase in alkalinity followed by a reduction with increasing time of aeration. A general observation in both series of batch experiments is that at prolonged aeration periods the alkalinity of the primary (control) sludge was much lower than the initial alkalinity of this sludge. The alkalinity of lime-primary sludges decreased to a value slightly lower than the initial value in Series I, and reached a minimum value slightly greater than the initial value in Series II (except for sludge D).

The alkalinity of all sludges studied in Series II (Figure 8) showed a tendency to stabilize at a constant value after about 10 - 15 days of aeration. Similar conditions were not reached in the Series I experiments (Figure 7) until at least 20 days and were not as obvious as in the Series II experiments. This difference in behaviour is probably due to the presence of specific industrial effluents in the original waste contributing differently to the forms of alkalinity present in the sludge studied in each series of the experiments and to the progress of digestion in each case.

In the semicontinuous loading experiments (Series III, IV and V), as shown in Figures 9 to 11, the alkalinity of the primary (control) sludge in digester A was much lower, and less stable, than that of the lime-primary sludge in digesters B, C and D at steady state. For the

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lime-primary sludge, in each of Series III and IV, the alkalinity values in digesters B, C and D were essentially similar at steady state, indicating a limited effect of detention time on the alkalinity of the sludge. In Series V, at steady state, this was true only for digesters C and D, which had detention times of 10 and 15 days, respectively; the alkalinity in digester B, which had a detention time of seven days, was slightly higher than that of digesters C and D. For practical reasons, the alkalinities of digesters B, C and D in each of the Series III, IV and V semicontinuous loading experiments could be represented by a single average value in each case.

Figures 9 to 11 show that for the lime-primary sludges at steady state operation the digested sludges in Series III, IV and V had average alkalinity values of 389, 504 and 669 mg/l as $CaCO_3$, respectively. The alkalinity data indicated that, unlike the pH, the alkalinity of the digested lime-primary sludge is dependent upon the initial pH and the alkalinity of the feed sludge. The higher the latter value is, the higher the alkalinity of the digested sludge would be.

As a result of aerobic digestion, the alkalinity of the primary (control) sludge in digesters A in Series III, IV and V was reduced from an overall average of about 300 mg/l as $CaCO_3$ in the raw (feed) sludge to an overall average of 33 mg/l as $CaCO_3$ in the digested sludge at steady state, for a detention period of 10 to 15 days. In contrast, the alkalinity values for the lime-primary sludges were increased as a result of digestion. In Series III, IV and V, the alkalinity values increased from overall averages in the raw (feed) sludges of 238, 290 and 532 mg/l as $CaCO_3$, respectively, to overall averages in the digested sludges at a steady state of 389, 504 and 669 mg/l as $CaCO_3$, respectively, for detention periods of 7 to 15 days.

3.2   Kinetics of Digestion

The kinetics of the aerobic digestion of the sludges in both the batch and semicontinuous loading experiments were dealt with generally as the rate of decomposition of the sludge total volatile solids (TVS), volatile suspended solids (VSS), and the reduction of the oxygen uptake rate of the sludge biomass.
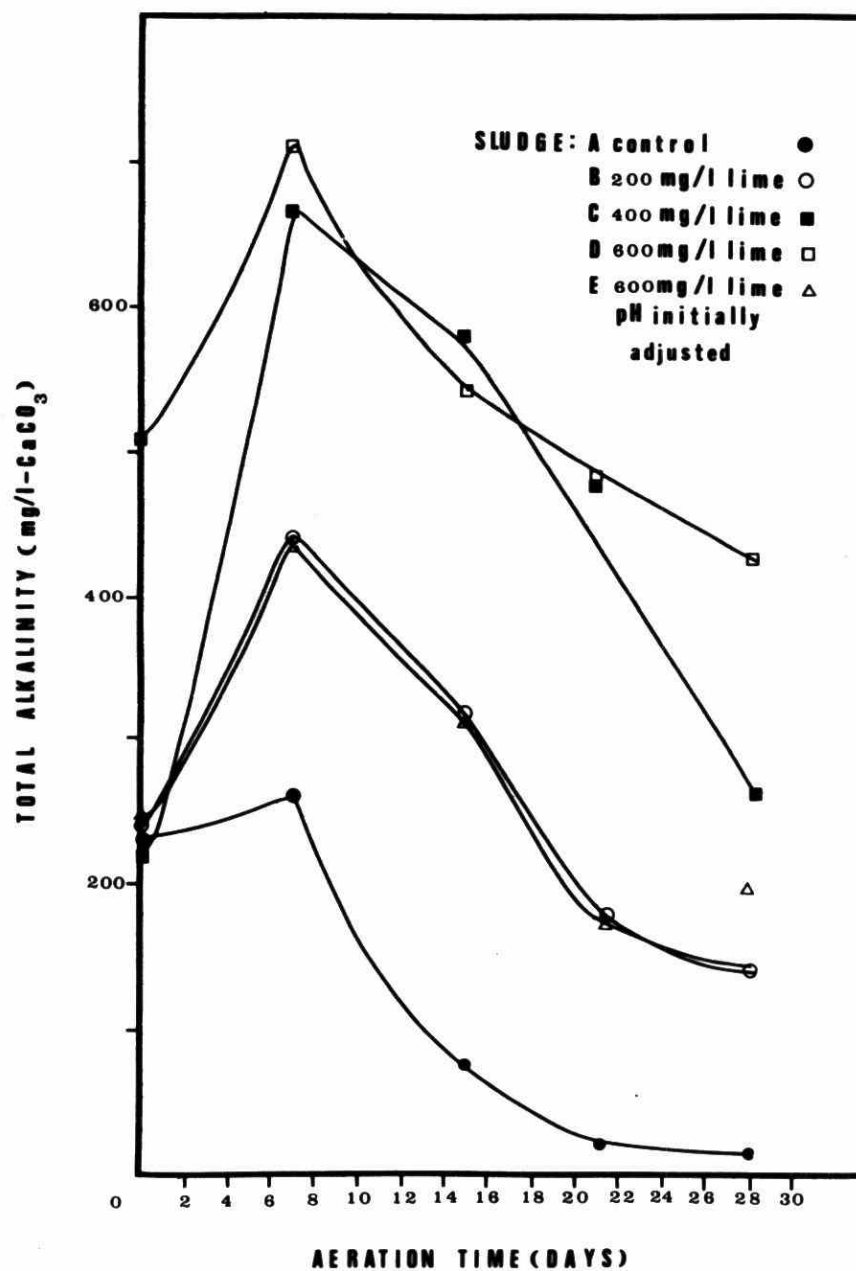
18

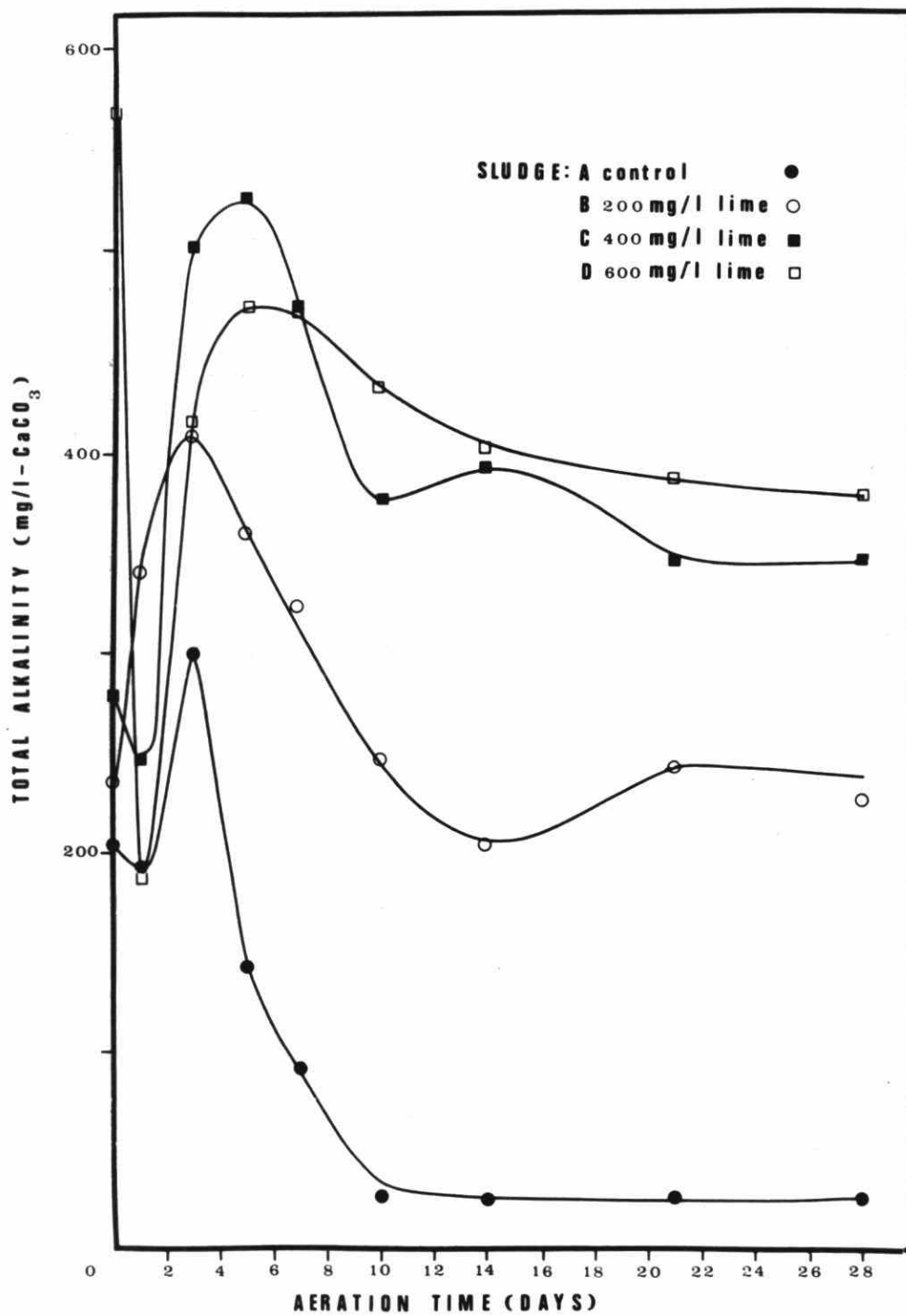FIGURE 7. CHANGES IN TOTAL ALKALINITY (SERIES I)

19

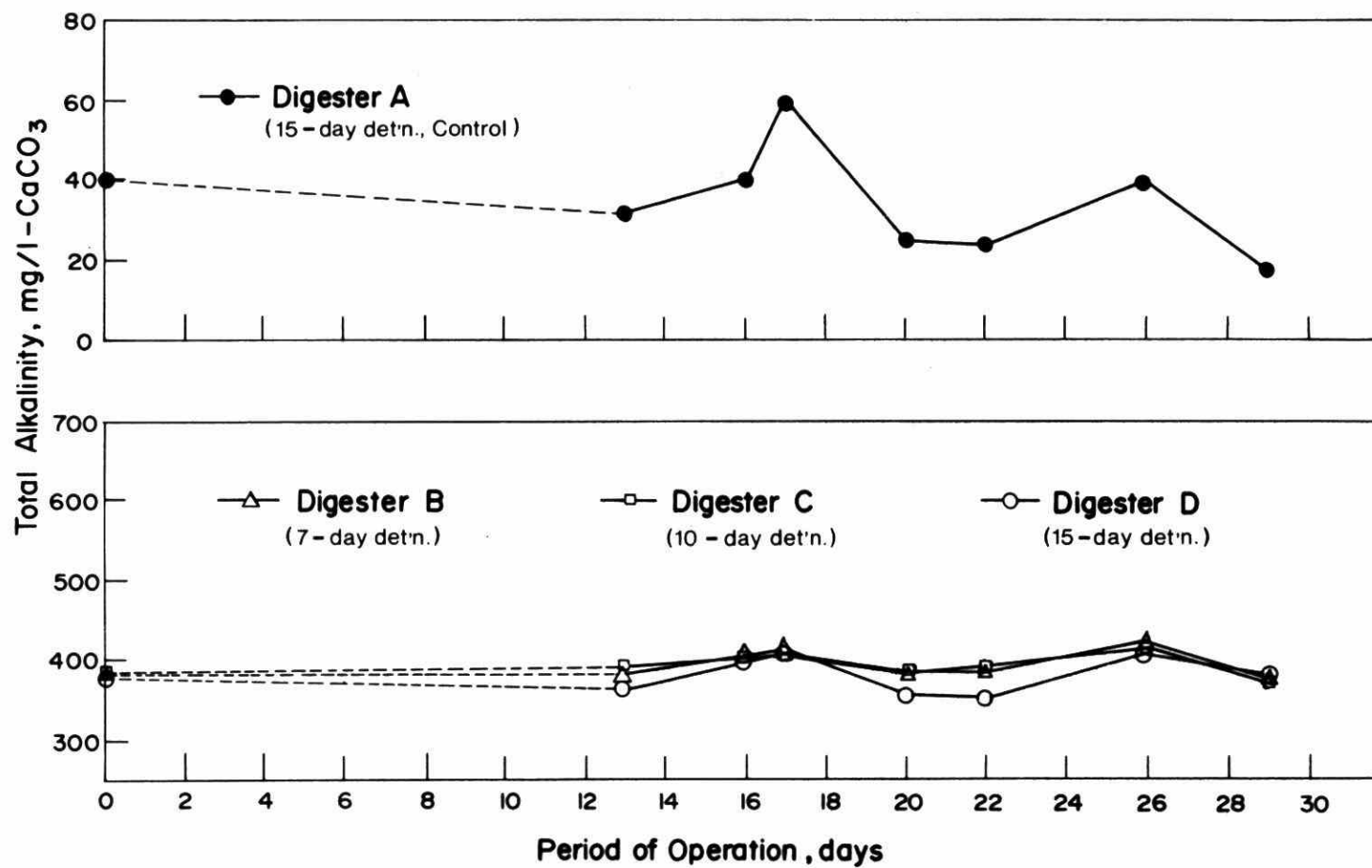FIGURE 8. CHANGES IN TOTAL ALKALINITY (SERIES II)

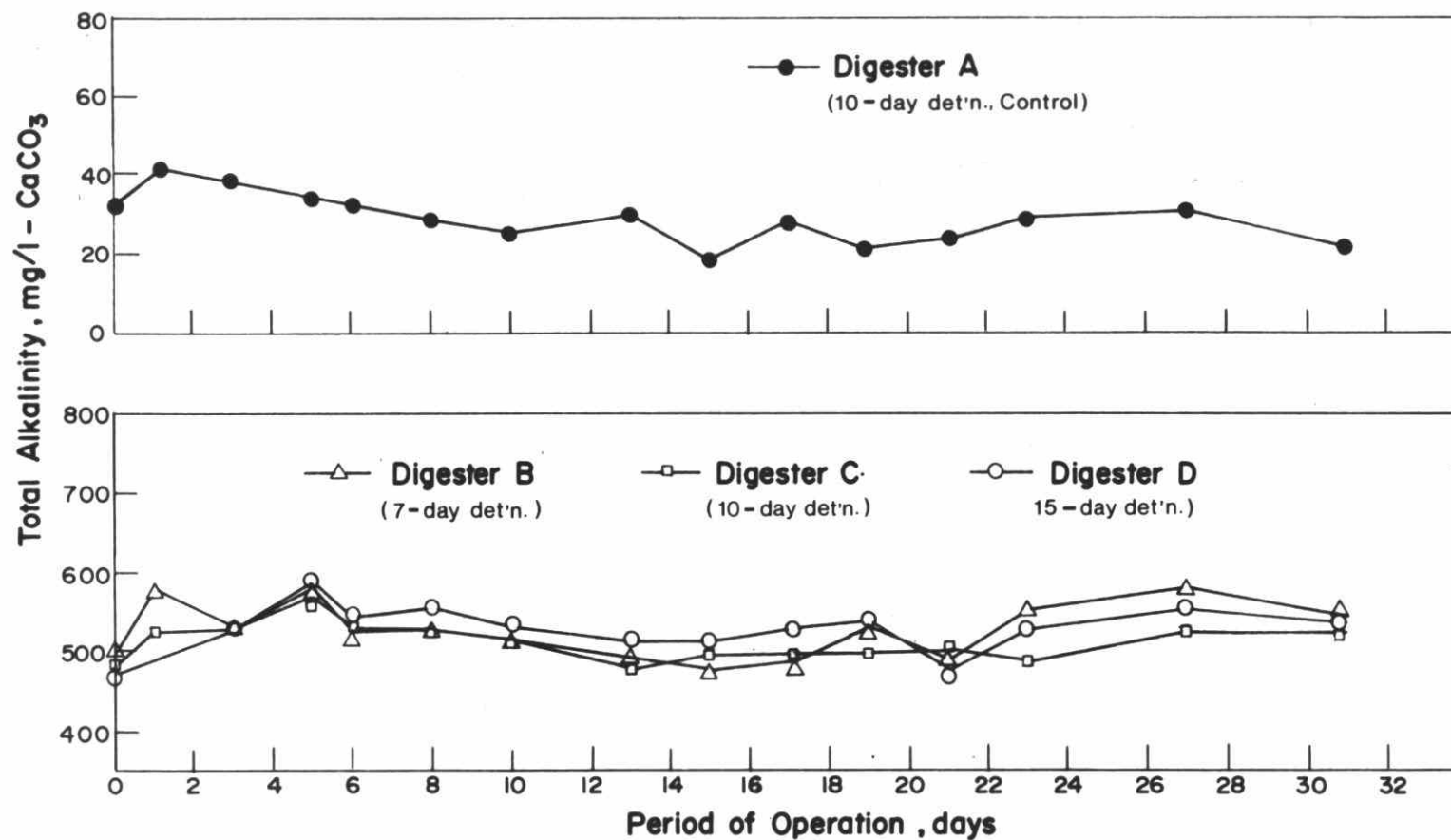FIGURE 9.   DIGESTER OPERATING DATA – CHANGES IN TOTAL ALKALINITY (SERIES III)

FIGURE 10. DIGESTER OPERATING DATA – CHANGES IN TOTAL ALKALINITY (SERIES IV)
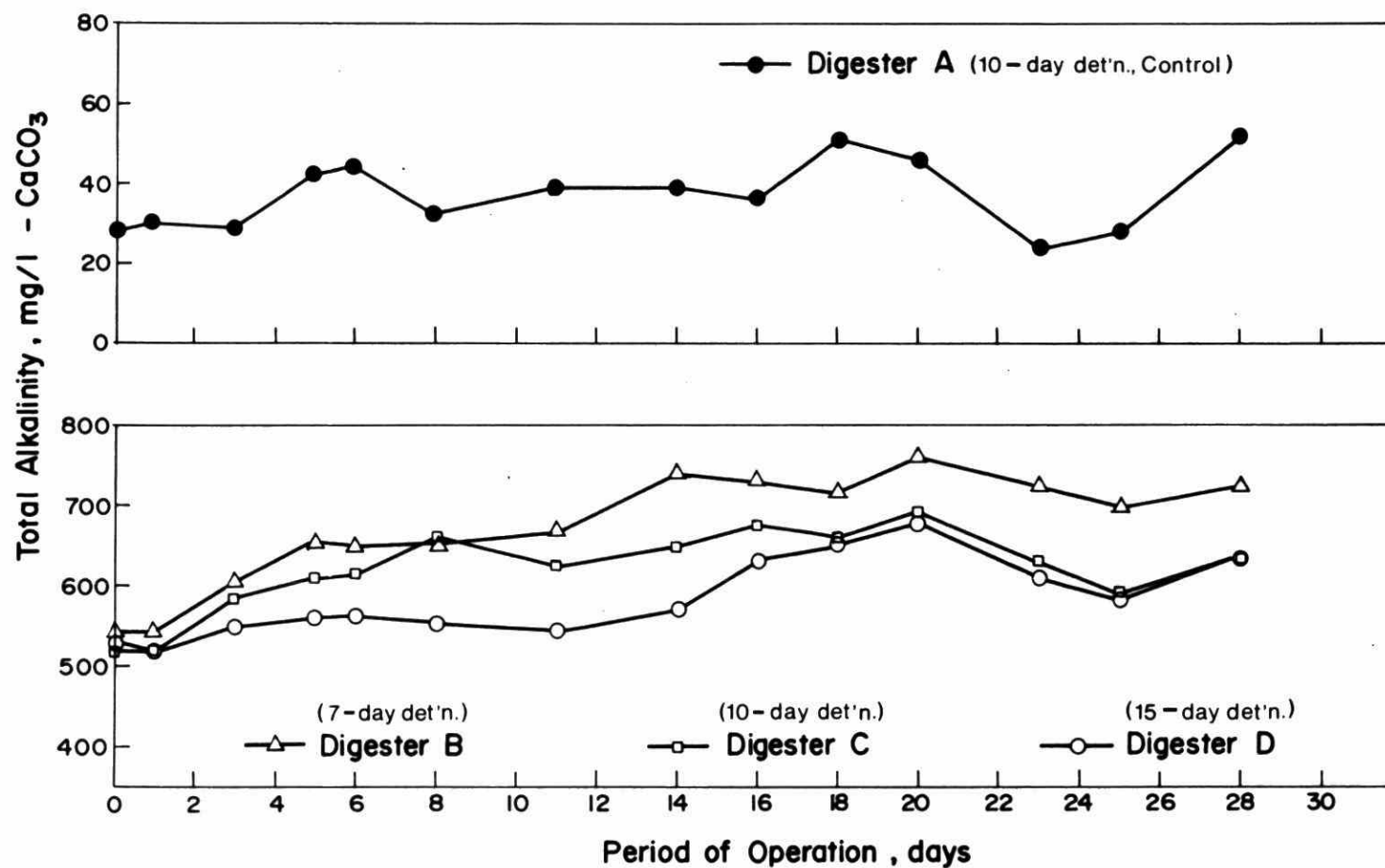
FIGURE 11. DIGESTER OPERATING DATA — CHANGES IN TOTAL ALKALINITY (SERIES $\overline{V}$)

The raw (feed) control primary sludge had percentages of TVS and VSS content which were higher than those of the raw (feed) lime-primary sludge. This is expected since the lime-primary sludge contains inorganic chemical precipitates resulting from the lime treatment of wastewater. Also, the percentages of TVS and VSS content of the feed lime-primary sludge decreased as the lime dose used for the chemical precipitation was increased.

The data obtained from the batch loading experiments on the decomposition of total volatile solids and volatile suspended solids as a function of time are shown graphically in Figure 12 (Series I) and Figure 13 (Series II). The rate of decrease of the sludge organic solids decreased as the aeration period increased. Aeration for more than 15 days resulted in only slight changes in volatile solids concentration. This was true for all sludges studied. The graphs show initial lag periods during which little active decomposition of organic sludge solids took place. This initial period may be described as a sludge activation period that served the purpose of acclimation of the sludge microorganisms to the existing environment. The initial lag period was short but lasted longer for sludges having a higher pH, the maximum lag period being four days.

To better visualize the functional dependence between the decomposition of organic sludge solids and the period of aeration, the oxidizable volatile suspended solids (VSS) data were correlated to the aeration time. The oxidizable (biodegradable) portion of VSS was obtained by subtracting the nonbiodegradable portion of the sludge VSS from the VSS concentration in the digester. The nonbiodegradable portion was approximated for each sludge from the graphical representation shown in Figure 12 (Series I) and Figure 13 (for Series II) as the value of VSS remaining at the time when essentially no further decrease in VSS took place. For primary sludge, the nonbiodegradable value· was about 69 percent of the initial VSS concentration in both the Series I and II experiments. For lime-primary sludge, the nonbiodegradable fraction of VSS was in the range of 62 to 66 percent, and in the range of 69 to 80 percent of the initial VSS concentration for Series I and II, respectively. Higher percentages of nonbiodegradable VSS were
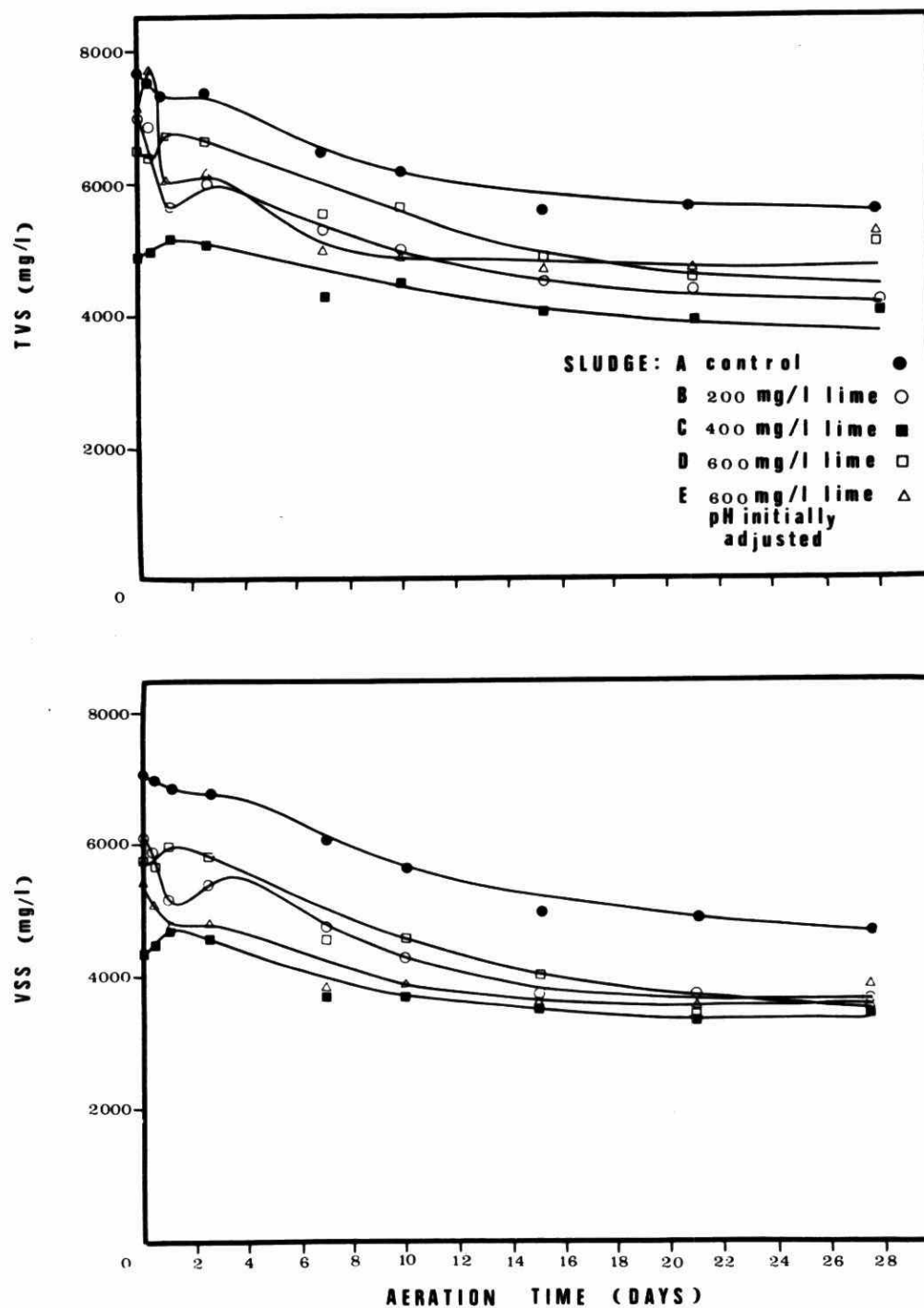
FIGURE 12. TOTAL VOLATILE SOLIDS (TVS) AND VOLATILE
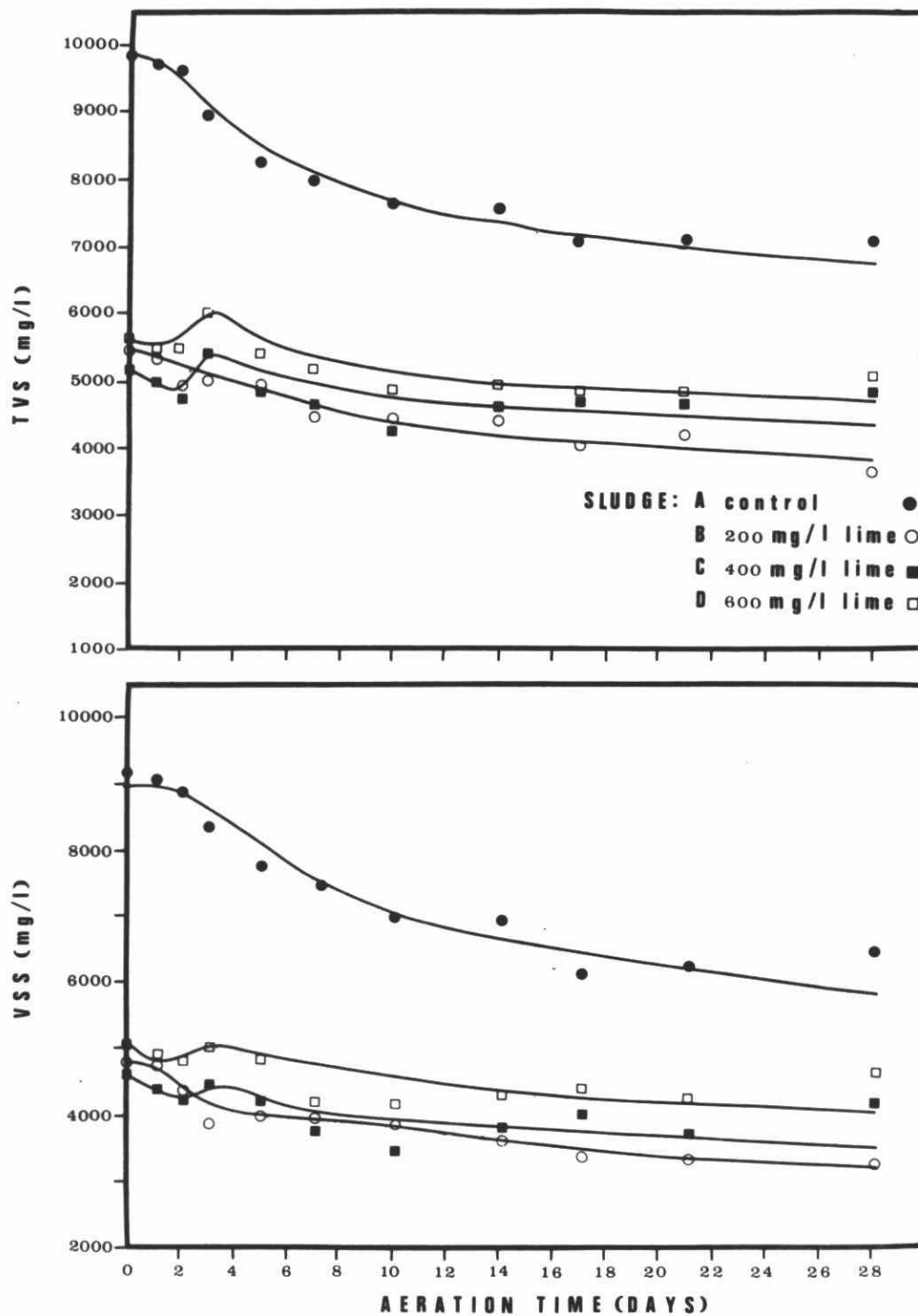SUSPENDED SOLIDS (VSS) VS AERATION TIME
(SERIES I)

25

FIGURE 13.   TOTAL VOLATILE SOLIDS (TVS) AND VOLATILE
SUSPENDED SOLIDS (VSS) VS AERATION TIME
(SERIES II)

26

reported for lime-primary sludges that were obtained by precipitation with higher dosages of lime.
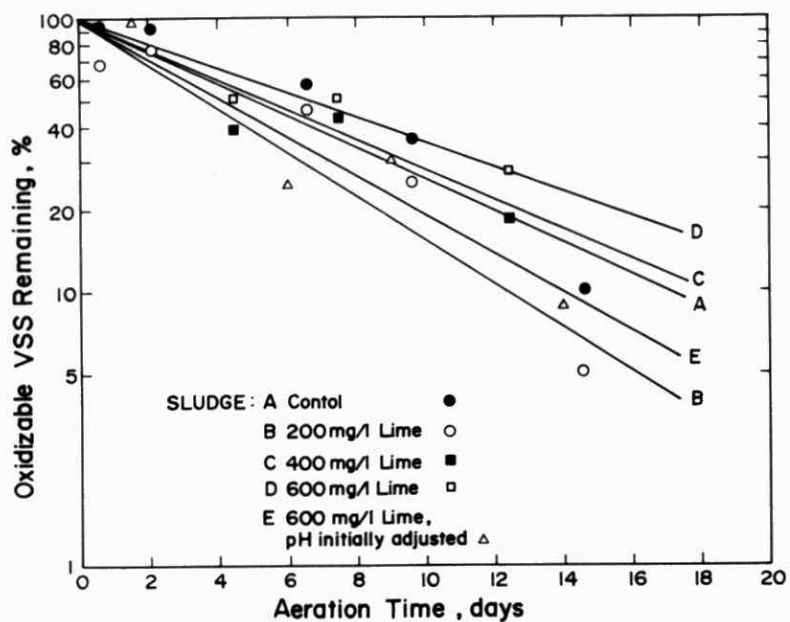
For all sludges studied, statistical analysis indicated a good linear correlation between the percent oxidizable VSS remaining and the aeration time if presented on semi-logarithmic plots as shown in Figures 14(a) and 14(b). The kinetics of the biochemical reaction were represented by the following first-order relationship:

$$\frac{VSS_t - VSS_n}{VSS_o - VSS_n} = e^{-k't} = 10^{-kt} \tag{1}$$

where: VSS_o = volatile suspended solids at time zero (mg/l)

VSS_t = volatile suspended solids at time t (mg/l)

VSS_n = nonbiodegradable volatile suspended solids (mg/l)

t = aeration time (days)

k,k' = reaction rate constants to the base 10 and base e, respectively (day^{-1}); $k = (k'/2.303)$.

The slopes of the lines shown in Figure 14(a) and 14(b) represent the values of the rate constant k for the different sludges studied. The data plotted in Figures 14(a) and 14(b) were fitted using the method of least squares and the values of k for different sludges were obtained. The values of k obtained for the sludges studied in the Series I and Series II batch experiments are given in Table 2.

The values of k for the control sludge A in the Series I and Series II experiments are similar. For the lime-primary sludges, B, C and D studied in the Series I and Series II experiments, lower k values were reported for sludges having a high initial pH. In Series I, the highest k value was observed for sludge obtained by raw sewage precipitation with 200 mg/l of $Ca(OH)_2$, namely sludge B. Although sludge B in Series II was also the result of precipitation with 200 mg/l of $Ca(OH)_2$, the k value reported in this case was lower than that reported for sludge B in Series I. The latter effect could be explained by the lower alkalinity of the raw sewage used in Series II which resulted in a much higher initial pH of sludge B in Series II than in Series I. Also, since two different raw sewage samples were used in these two series of experiments, the possibility that the different nature of the sludge

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Oxidizable VSS Remaining, %

100
80
60

40

20

10

5

D
C
A
E
B

SLUDGE: A Contol ●
B 200 mg/l Lime ○
C 400 mg/l Lime ■
D 600 mg/l Lime ▢
E 600 mg/l Lime,
pH initially adjusted △

0 2 4 6 8 10 12 14 16 18 20

Aeration Time , days

OXIDIZABLE VOLATILE SUSPENDED SOLIDS (VSS)
REMAINING VS. AERATION TIME (SERIES I)

FIGURE 14(a)

100
80
60

40

20

10

5

D
C
A
B

SLUDGE: A Control ●
B 200 mg/l Lime ○
C 400 mg/l Lime ■
D 600 mg/l Lime ▢

0 2 4 6 8 10 12 14 16 18 20
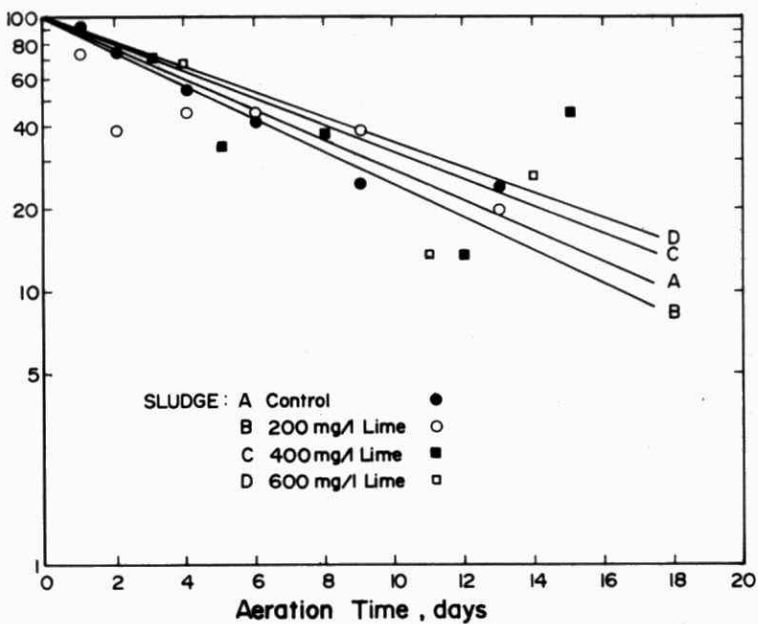
Aeration Time , days

OXIDIZABLE VOLATILE SUSPENDED SOLIDS (VSS)
REMAINING VS. AERATION TIME (SERIES II)

FIGURE 14(b)

TABLE 2. DECOMPOSITION OF VOLATILE SUSPENDED SOLIDS
(Process Kinetics at 20°C)

Type of Sludge	Series I		Series II	
	Initial pH of Sludge	Oxidizable VSS Decomposition rate (k, base 10) (day^{-1})	Initial pH of Sludge	Oxidizable VSS Decomposition rate (k, base 10) (day^{-1})
Sludge A (control)	7.81	0.058	7.25	0.055
Sludge B (200 mg/l lime)	9.86	0.081	10.24	0.060
Sludge C (400 mg/l lime)	11.30	0.055	11.45	0.050
Sludge D (600 mg/l lime)	11.85	0.050	11.90	0.047
Sludge D (600 mg/l lime, pH initially adjusted)	7.40	0.071	-	-

studied in each series might be responsible for the difference in kinetics cannot be ruled out.

The kinetics data also indicated that sludge B (lime-primary sludge precipitated with 200 mg/l) in Series I showed higher digestion rate than the control sludge A (primary sludge). Sludge E (lime-primary sludge precipitated with 600 mg/l lime with pH initially adjusted) also showed higher digestion rate than sludge A. Finally, the results from the batch loading experiments suggested that detention times up to 15 days are significant for volatile solids decomposition.

The results from the semicontinuous loading experiments (Series III, IV and V) are shown in Figures 15, 16 and 17 for the digested sludge during the operating period. In these series of experiments, variations in the solids concentration and in the percentages of TVS and VSS content of the feed sludges used throughout each experiment were often minimal. This helped in the development of steady state (equilibrium) conditions within a reasonable time. For kinetic studies, the VSS concentrations of the digested and feed sludges were averaged over a period of time when steady state conditions prevailed and little day-to-day variation occurred.

The percentage reductions in TVS and VSS were calculated for the sludges studied in Series III, IV and V at different detention times. The formula used in the calculations is that found in the WPCF Manual of Practice No. 11 (1970):

Percent reduction of volatile matter =

$$\left[1 - \frac{(FS)feed}{(VS)feed} \times \frac{(VS)digested}{(FS)digested} \right] \times 100 \qquad (2)$$

where: FS = % fixed solids in sludge
          VS = % volatile solids in sludge.

Figures 18(a) and 18(b) show respectively the percentage reduction in TVS and VSS as a function of detention time in the digesters.

The kinetics of VSS decomposition in the semicontinuous loading experiments was also studied. For each of Series III, IV and V, the nonbiodegradable fraction of VSS was approximated by plotting the time averaged VSS remaining in each digester at steady-state
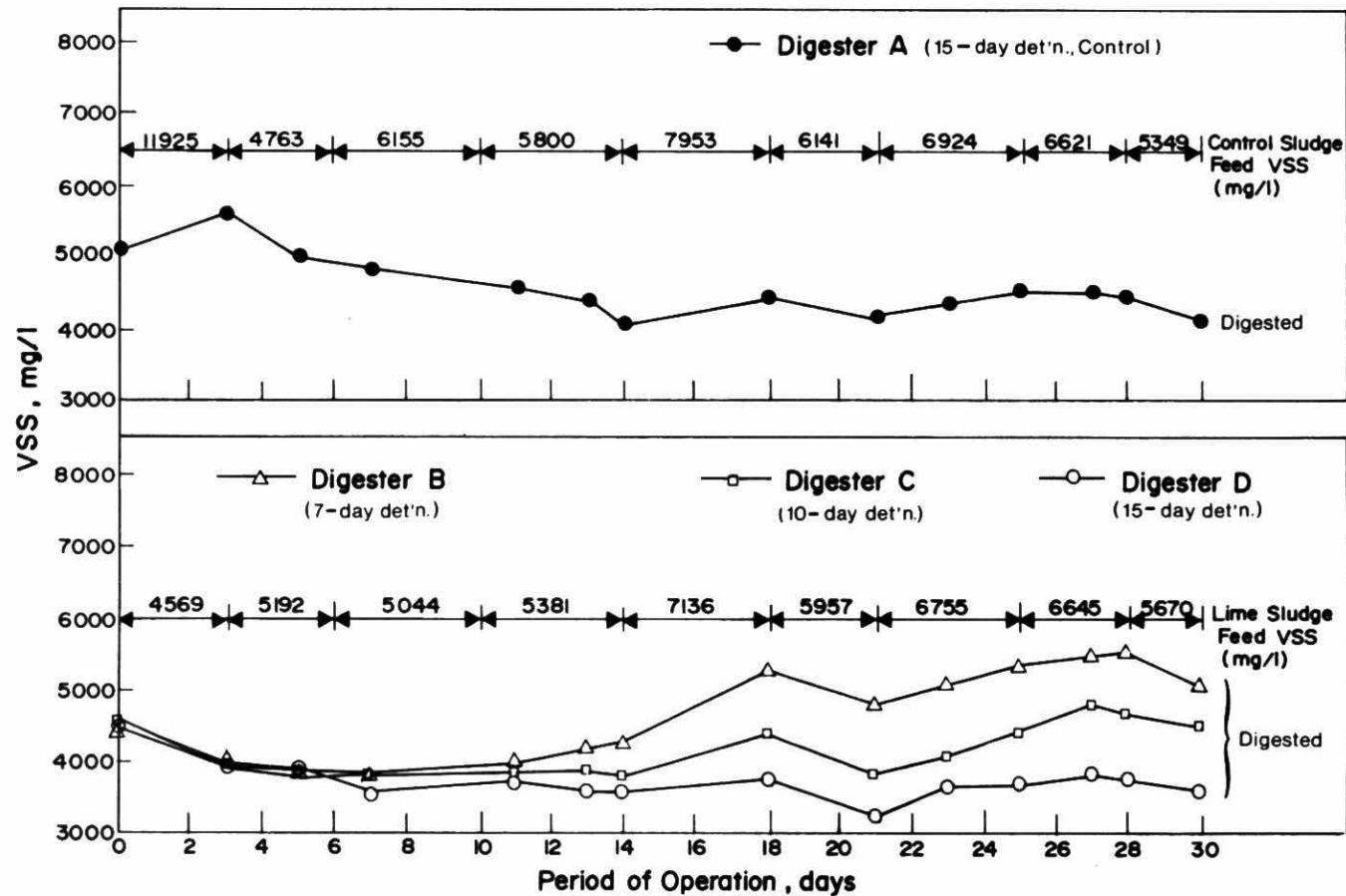
30

FIGURE 15. DIGESTER OPERATING DATA – SLUDGE VOLATILE SUSPENDED SOLIDS (VSS) (SERIES III)
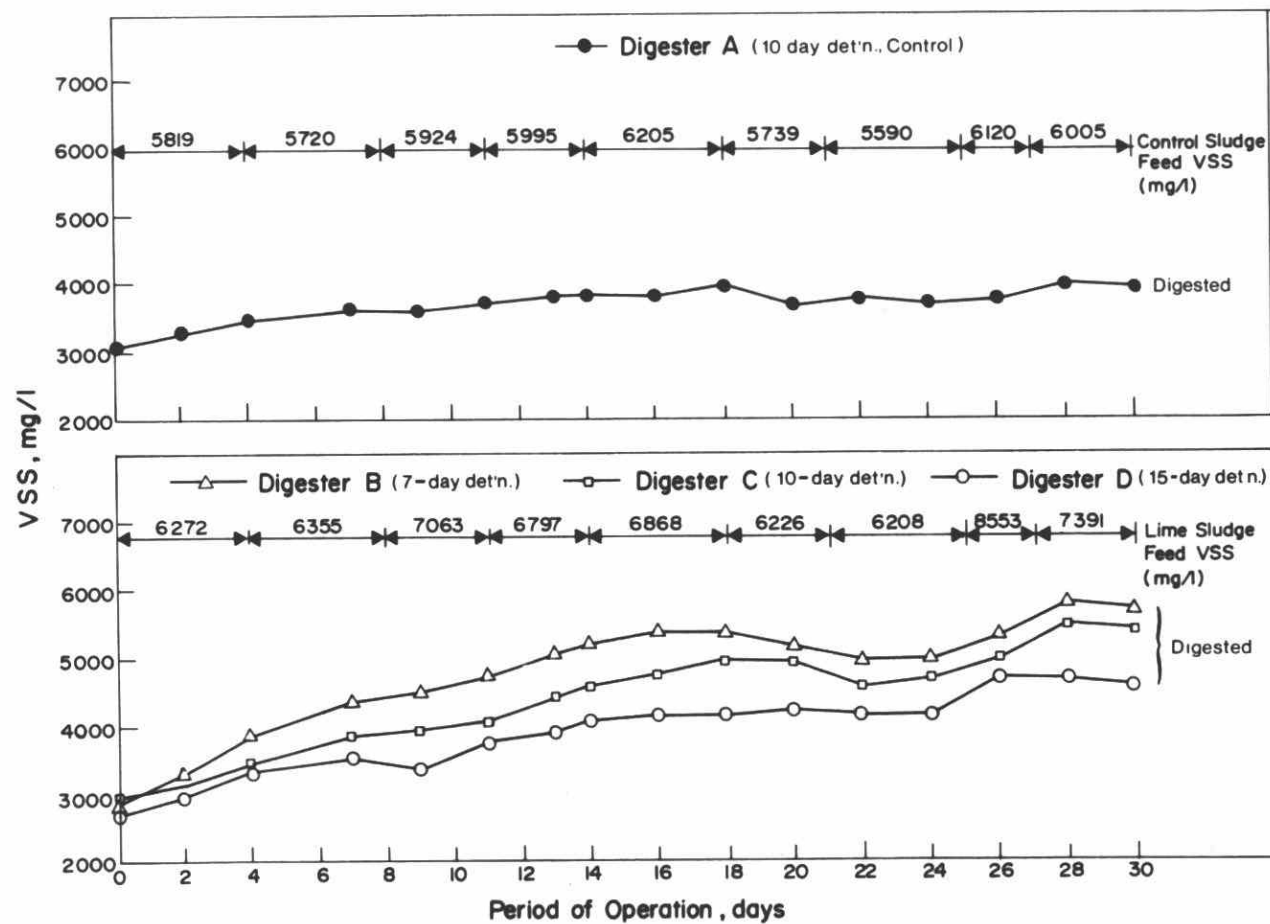
31

FIGURE 16. DIGESTER OPERATING DATA- SLUDGE VOLATILE SUSPENDED SOLIDS (VSS) SERIES IV
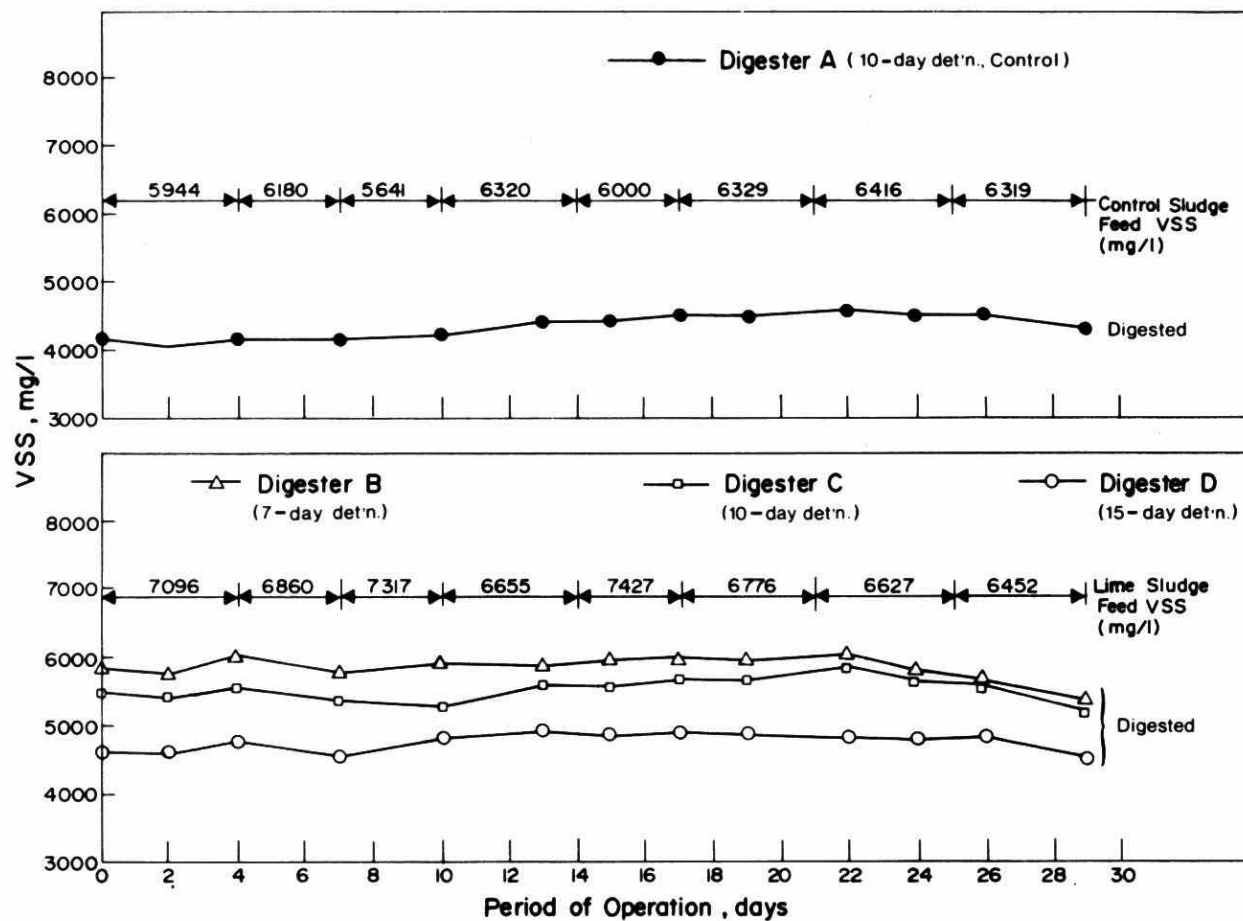
32

FIGURE 17. DIGESTER OPERATING DATA – SLUDGE VOLATILE SUSPENDED SOLIDS (VSS) SERIES ⅴ

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condition as a function of detention time and extrapolating the resulting plots to the point where no further reduction in VSS remaining occurred.

The fractions of nonbiodegradable VSS in the feed sludges approximated this way were 52, 60 and 67 percent for lime-primary sludges studied in the Series III, IV and V experiments, respectively. The VSS of the primary (control) feed sludge studied had a 63 percent nonbiodegradable fraction. For each sludge, the biodegradable VSS remaining at a particular time was obtained by subtracting the nonbiodegradable fraction from the VSS remaining at this particular time.

The biodegradable VSS data obtained for the lime-primary sludges during digestion in Series III, IV and V were fitted to kinetic models in order to obtain the rate constant for the decomposition of VSS. The removal of volatile suspended solids vs detention time agreed fairly well with a first order biochemical reaction kinetics for which equation (1) was previously presented. A good correlation was found between the logarithm of biodegradable VSS remaining vs detention time. The correlation coefficients obtained were 0.957, 0.978 and 0.923 for the data from Series III, IV and V, respectively. The values of k (base 10) obtained were 0.060, 0.054 and 0.048 (day^{-1}) at 20°C for the lime-primary sludges studied in Series III, IV and V of the semicontinuous experiments, respectively, compared to a value of 0.56 for the primary control sludge.

The results from the semicontinuous experiments (Series III, IV and V) agreed fairly well with those obtained from the batch experiments (Series I and II). The data on solids reduction (Figures 18a and 18b) and on the kinetics of solids decomposition in the semicontinuous experiments show that the lime-primary sludge used in Series III (initial pH of 9.5 - 10), which resembled sludge B studied in the batch experiments, was superior to the primary (control) sludge. A possible explanation for the better digestion kinetics for the lime-primary sludge is that the lime-primary sludge substrate contained more easy-to-digest biodegradable organics that were precipitated from the raw wastewater with lime. This is shown by the lower nonbiodegradable VSS fraction found for this lime-primary sludge as reported earlier. Hydrolysis of the complex substrate in the lime-primary sludge might have also occurred at high pH.
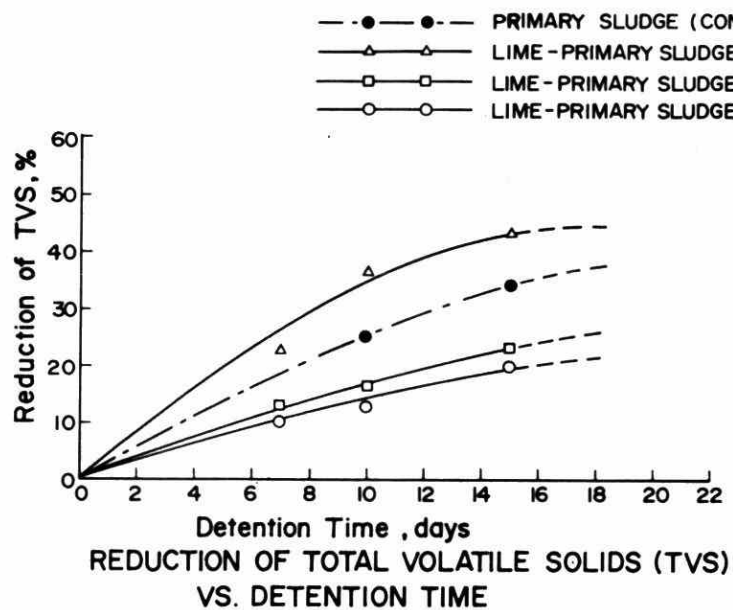
REDUCTION OF TOTAL VOLATILE SOLIDS (TVS)
VS. DETENTION TIME

FIGURE 18(a)

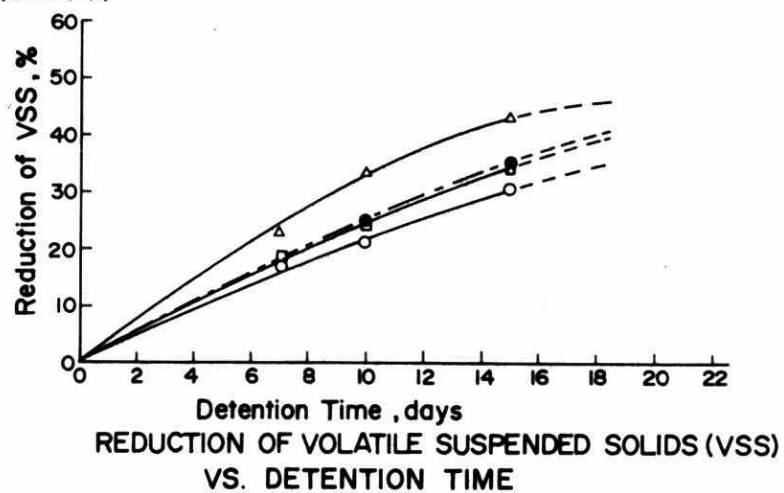REDUCTION OF VOLATILE SUSPENDED SOLIDS (VSS)
VS. DETENTION TIME

FIGURE 18(b)

The semicontinuous loading experiments also showed that the lower the initial pH value of the lime-primary sludge (precipitated with lower lime dosages), the better the digestion kinetics. This can be seen by comparing the sludges studied in Series III, IV and V. However, similar values were observed for the operating pH in digesters treating primary-lime sludges in Series III, IV and V, independent of the initial pH value of the sludge feed. This suggests that another factor involved in the digestion process is more important. The alkalinity of the lime-primary sludge during digestion, which was different for the different sludges studied in Series III, IV and V, is most likely a more important factor. A good correlation exists between the VSS decomposition rate constant k and the total alkalinity during aerobic digestion of lime-primary sludges as shown in Figure 19. This is true for the range of alkalinity values studied.

Similar observations from the batch loading experiments also support this finding, indicating that the total alkalinity during aerobic digestion of lime-primary sludges is an important factor affecting the solids digestion kinetics. The lower the alkalinity during digestion, the better the digestion kinetics. The high alkalinity or calcium concentration during aerobic digestion affects the sludge microbial population; an effect that might offset the advantage of the presence of the more easy-to-degrade substrate of the lime-primary sludge compared to the primary sludge. This may explain the reason for the lower digestion kinetics of the lime-primary sludges C and D in the batch experiments and the sludges used in Series IV and V of the semicontinuous experiments compared to their respective primary (control) sludges.

The digestion data on chemical oxygen demand (COD) of the sludge are in good agreement with those on sludge organic solids in that similar observations on the progress of digestion of the different sludges were made. The chemical oxygen demand data for different sludges are presented in Figures 20 to 23.

The oxygen utilization by sludge microorganisms is a measure of the biological activity of the sludge. Figures 24 and 25 show the change in the oxygen uptake rates of the aerobically digested sludge with aeration time in the batch experiments. In the Series I experiments

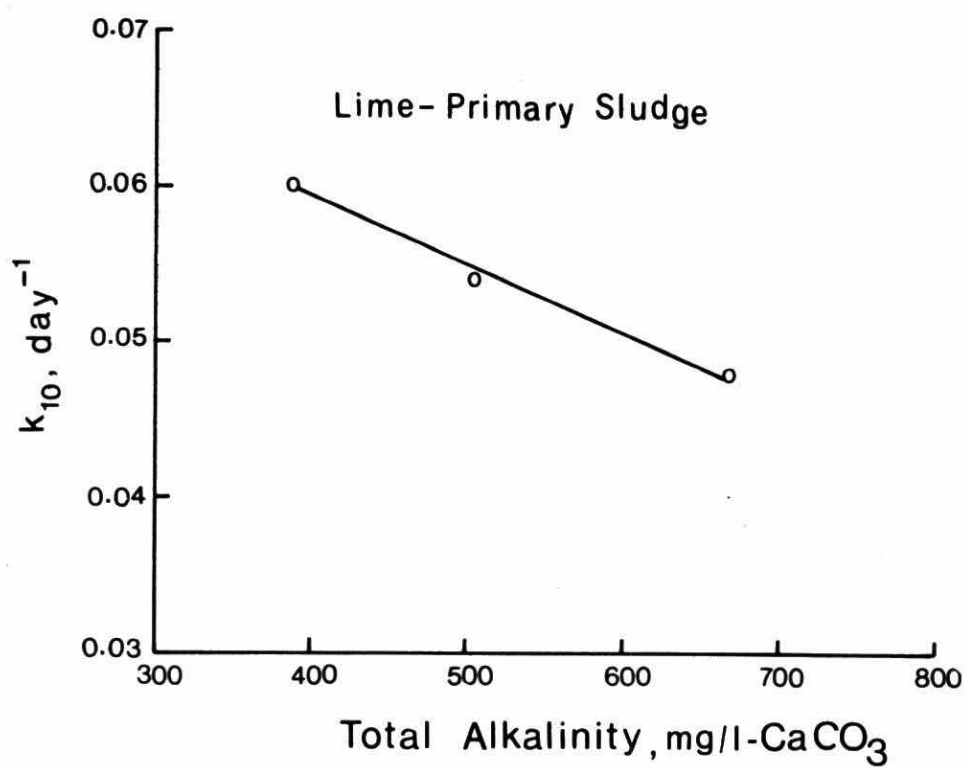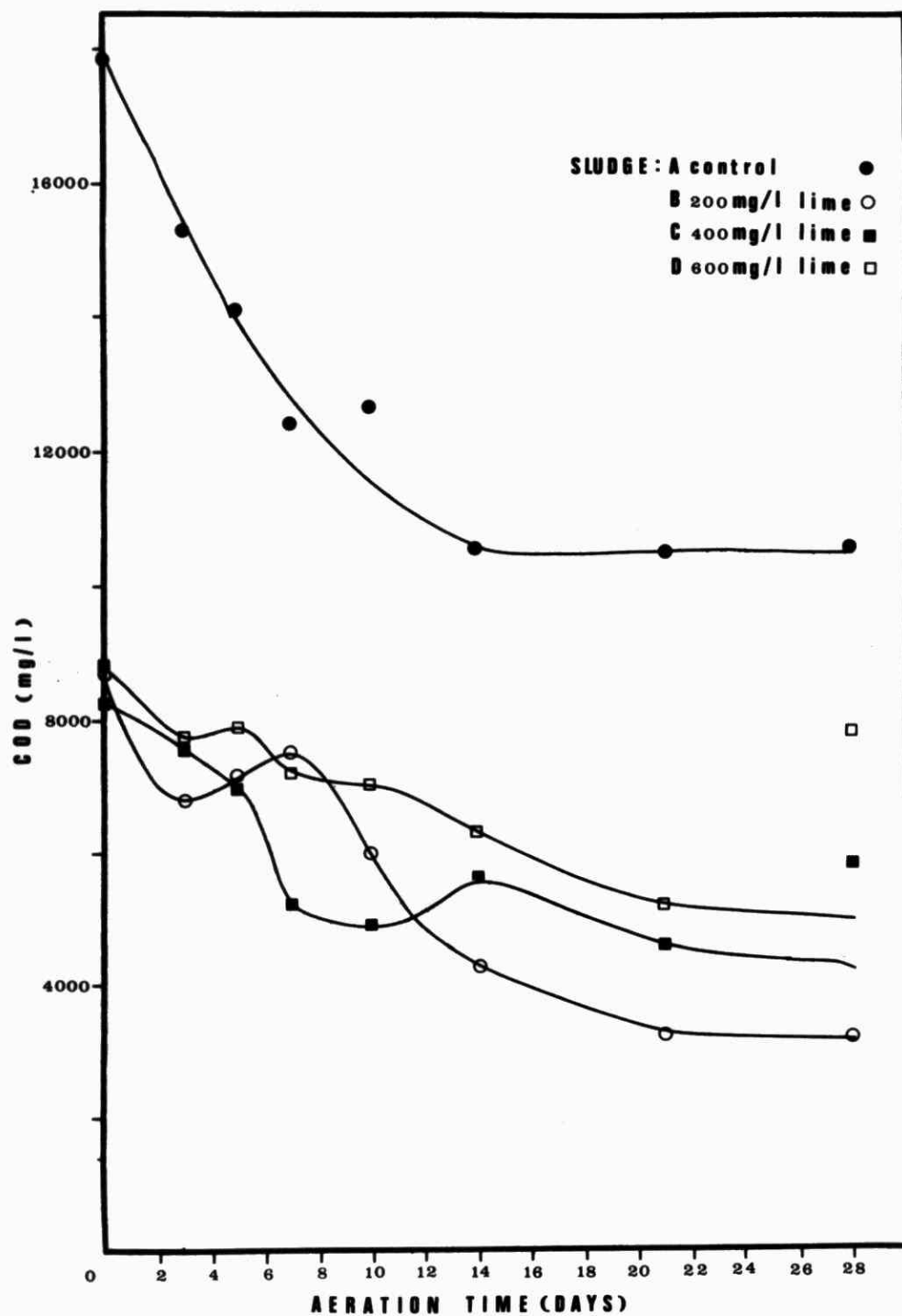FIGURE 19.　　RATE CONSTANT k_{10} at 20°C VS
TOTAL ALKALINITY

FIGURE 20. SLUDGE CHEMICAL OXYGEN DEMAND (COD) VS AERATION TIME
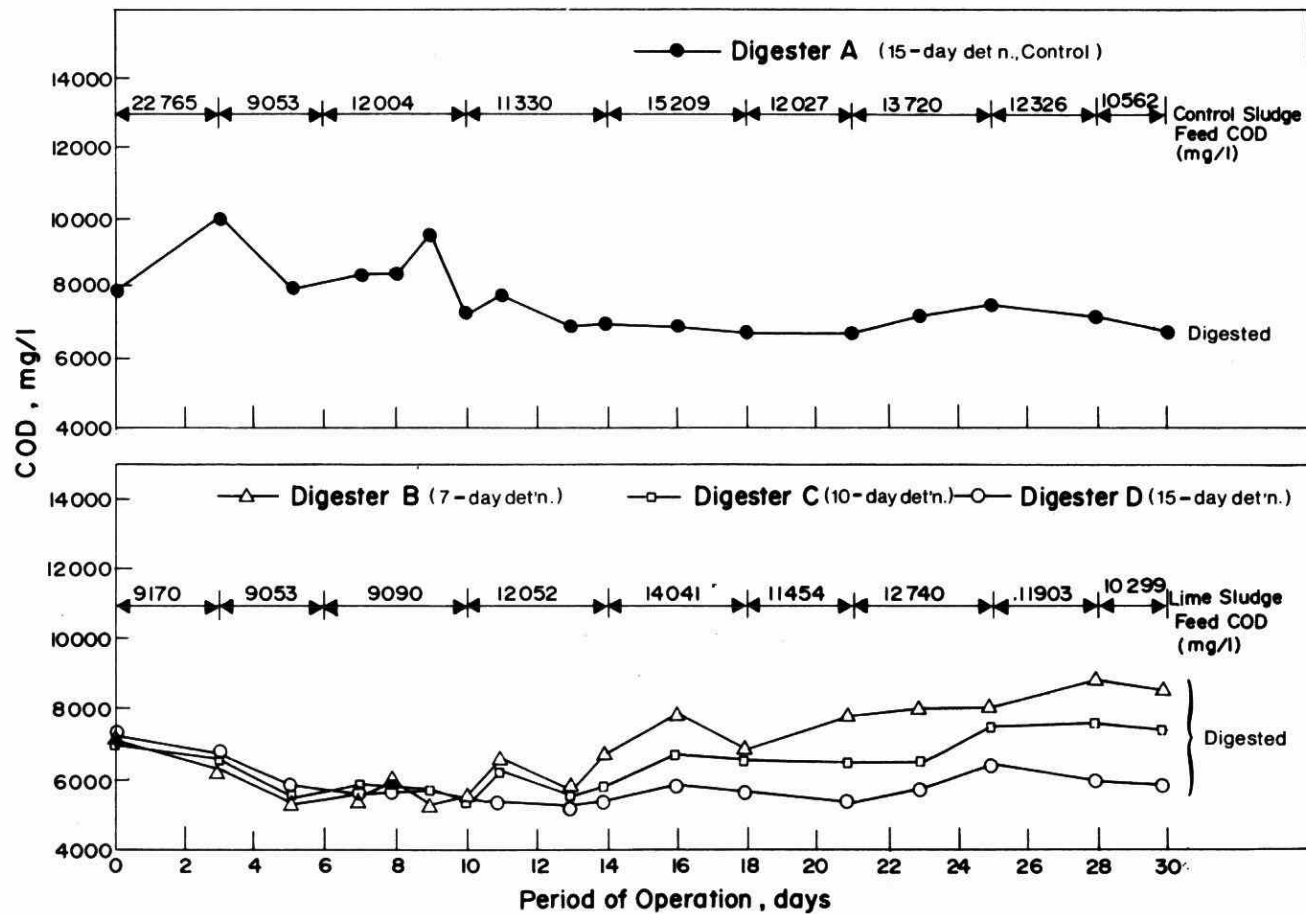(SERIES II)

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FIGURE 21. DIGESTER OPERATING DATA– SLUDGE CHEMICAL OXYGEN DEMAND (COD) (SERIES III)
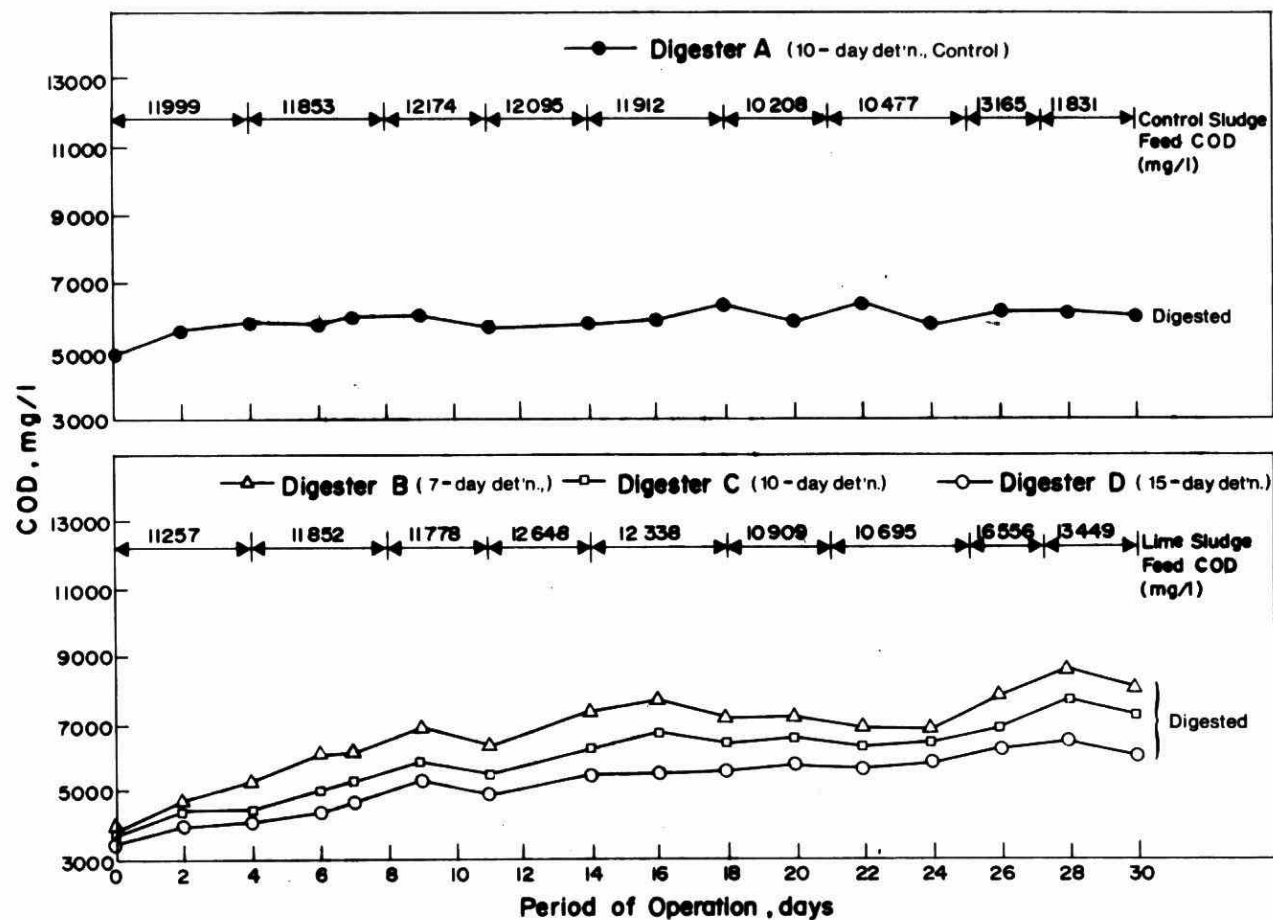
39

FIGURE 22. DIGESTER OPERATING DATA—SLUDGE CHEMICAL OXYGEN DEMAND (COD) (SERIES IV)
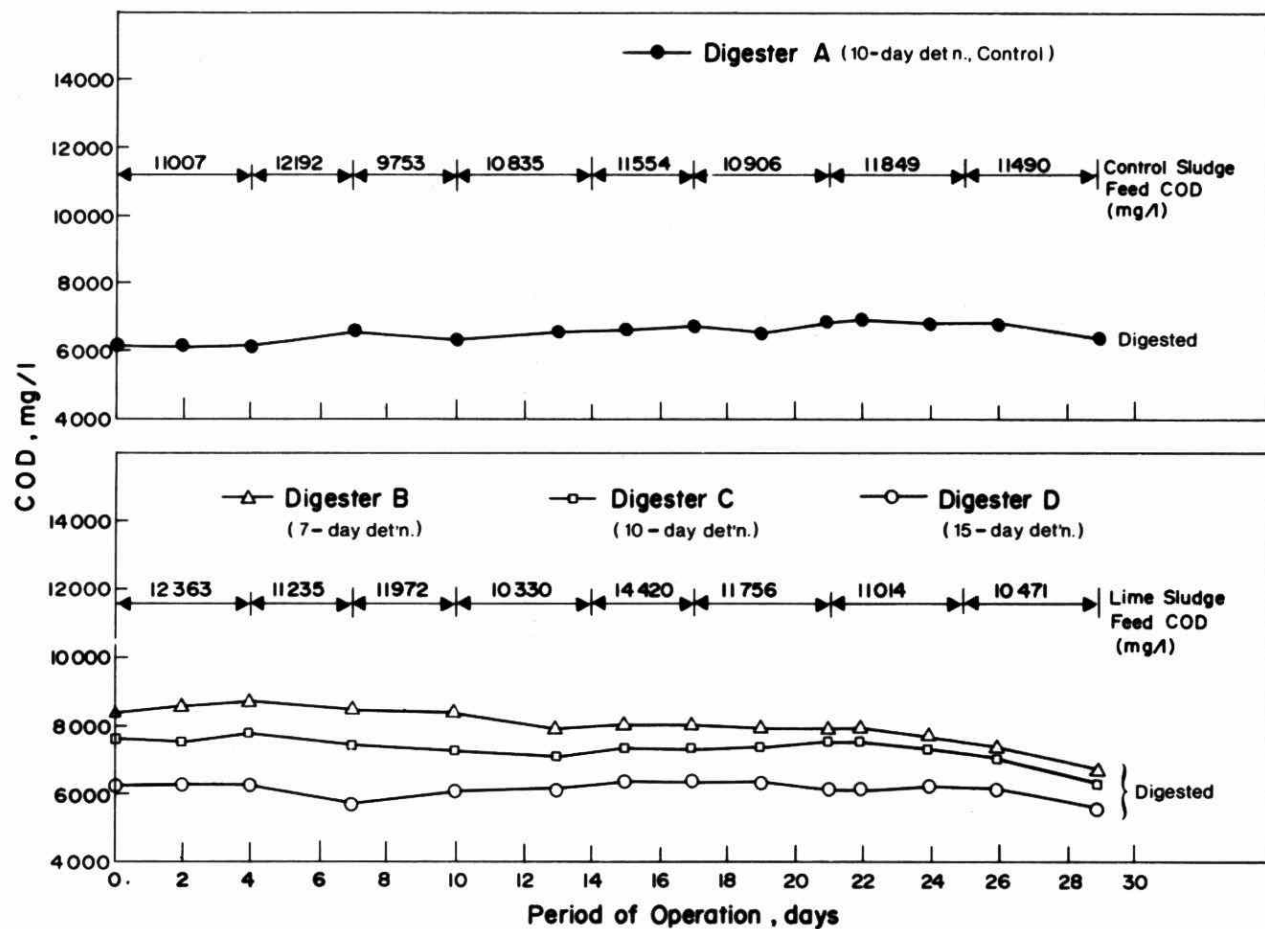
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FIGURE 23. DIGESTER OPERATING DATA — SLUDGE CHEMICAL OXYGEN DEMAND (COD) (SERIES Ⅴ)

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(Figure 24) a distinct stabilization of all the sludges studied occurred after 15 days of batch aeration. A similar stabilization was achieved in Series II for the control sludge (Figure 25) but the lime-primary sludges studied in this series of the experiments showed further decreases in the oxygen uptake rates at prolonged times of aeration.

Figures 26 to 28 show the oxygen uptake operating data for digested sludges in the semicontinuous loading experiments. For the lime-primary sludges studied in Series III, IV and V, digesters having shorter detention times produced sludges that had higher oxygen uptake rates (less stabilized). Primary (control) sludges generally showed slightly lower oxygen uptake rates than lime-primary sludges digested for similar detention periods. However, it should be noted that the feed lime-primary sludges often had higher oxygen uptake rates than the feed primary (control) sludges.

The sludges digested in the batch experiments (Series I and II) showed lower specific oxygen uptake rates than sludges digested in the semicontinuous loading experiments at similar digestion times. A possible explanation is that in the semicontinuous loading of digesters, new fresh feed sludges with high organic substrate concentrations and high oxygen uptake rates are fed daily to the digesters, at the same time stabilized sludges are withdrawn daily. Thus, shorter feed-starvation cycles are obtained in the semicontinuous system as compared with the batch system, creating conditions of higher substrate concentration and microbial activity in the semicontinuous system. This results in higher oxygen uptake rates of the sludge in the semicontinuous digester system.

The interpretation of the oxygen uptake data should be cautiously made since the oxygen uptake measurements do not differentiate between the amount of oxygen utilized for the exogenous substrate metabolism and that utilized for the endogenous metabolism during aerobic digestion of these types of primary sludges. Moreover, microscopic observations made on these sludges indicated differences in the predominance of species of the heterogenous populations in the digesters treating different sludges and at different stages of digestion. Detailed investigations into these aspects were beyond the scope of this study.
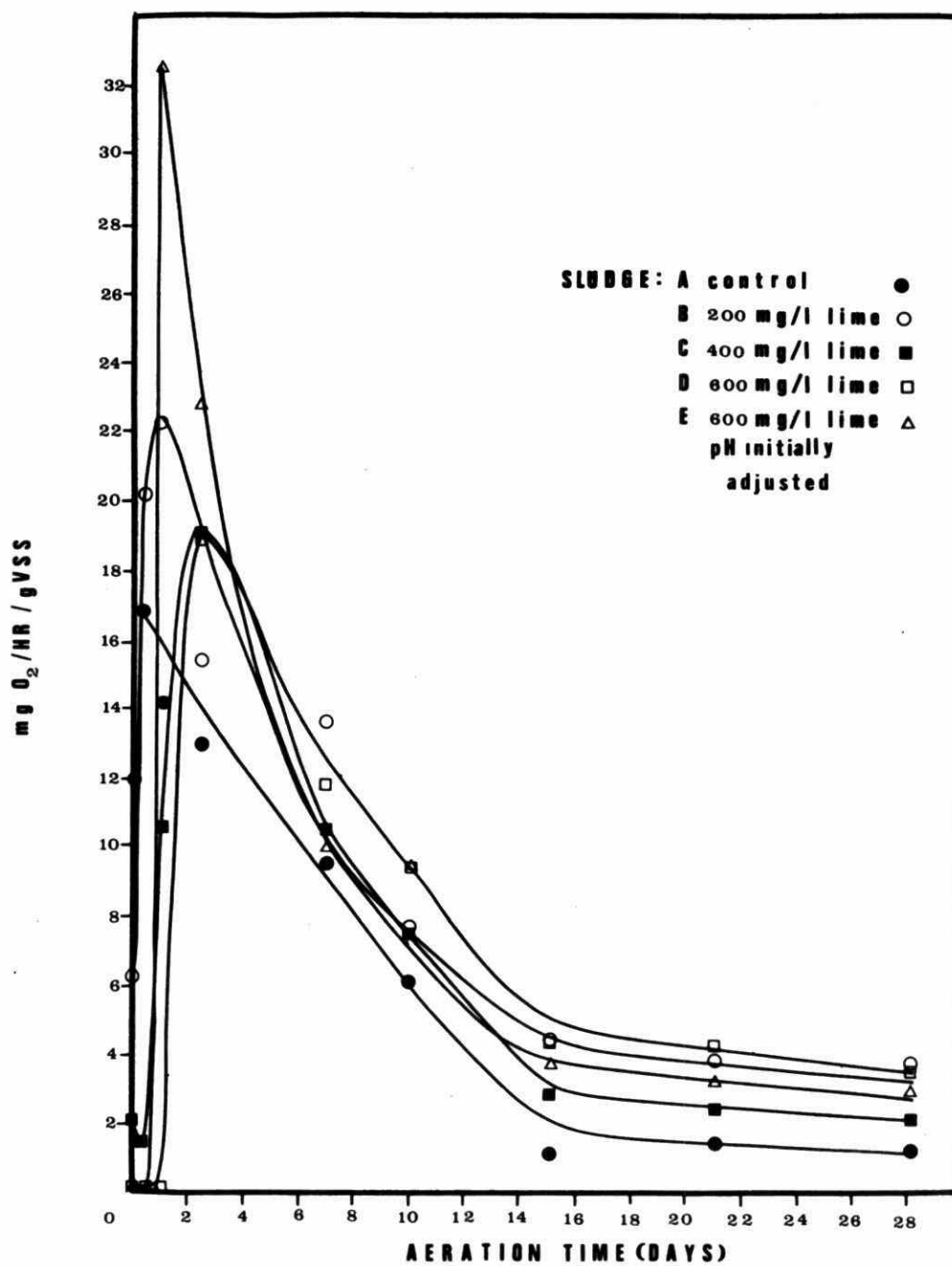
42

FIGURE 24. OXYGEN UPTAKE RATES AT 20°C VS AERATION TIME
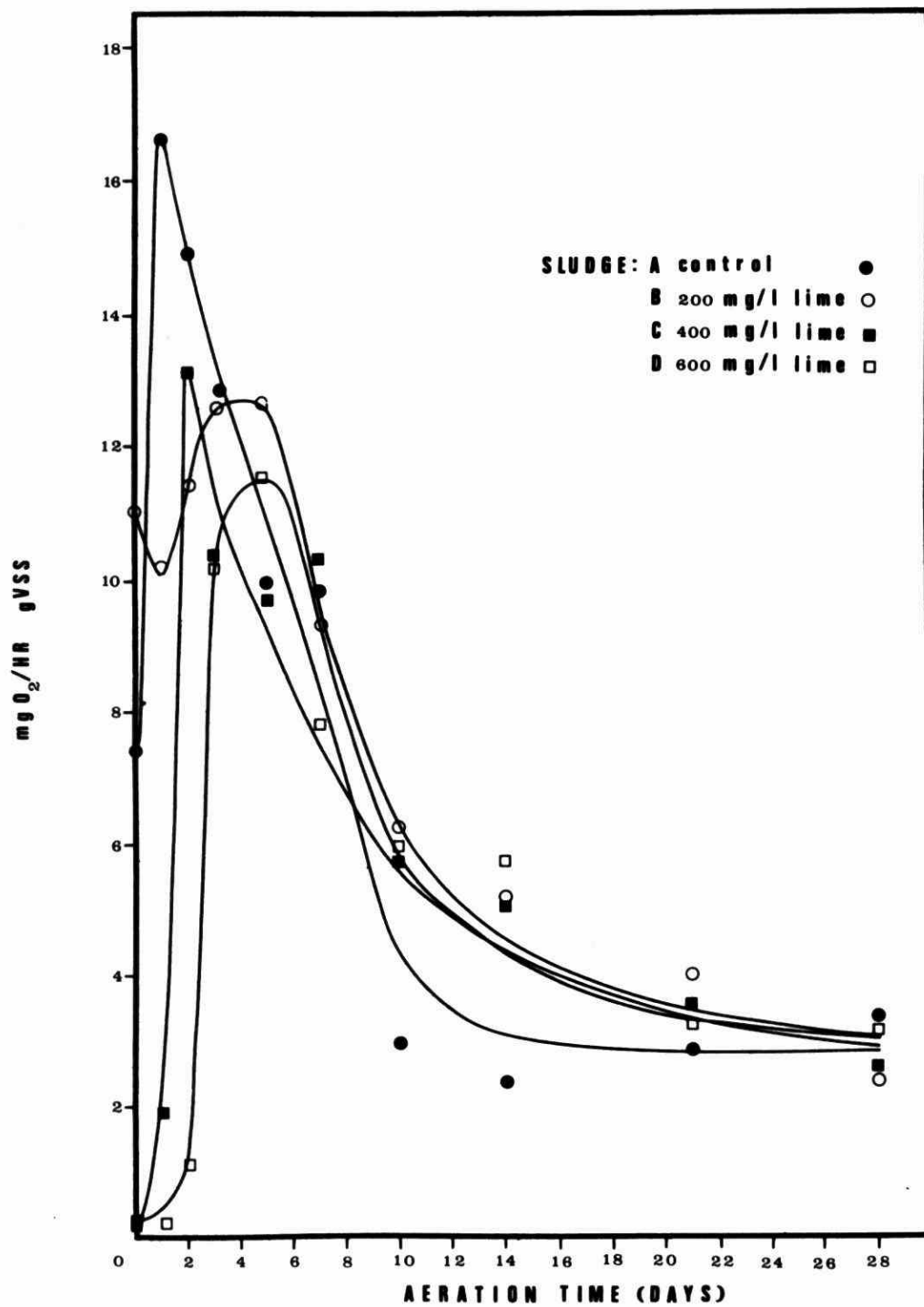(SERIES I)

43

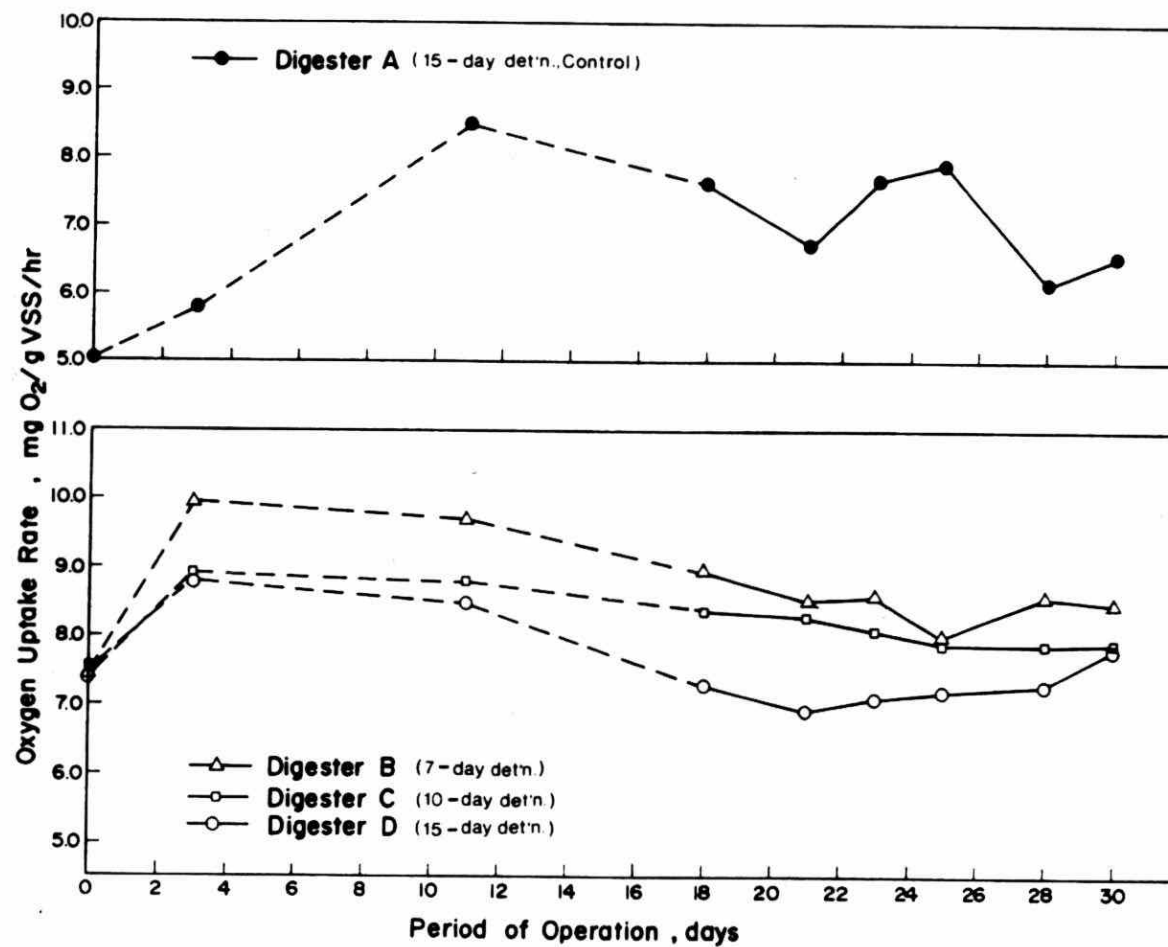FIGURE 25.   OXYGEN UPTAKE RATES AT 20°C VS AERATION TIME
(SERIES II)

44

FIGURE 26. DIGESTER OPERATING DATA – OXYGEN UPTAKE RATE AT 20°C (SERIES III)
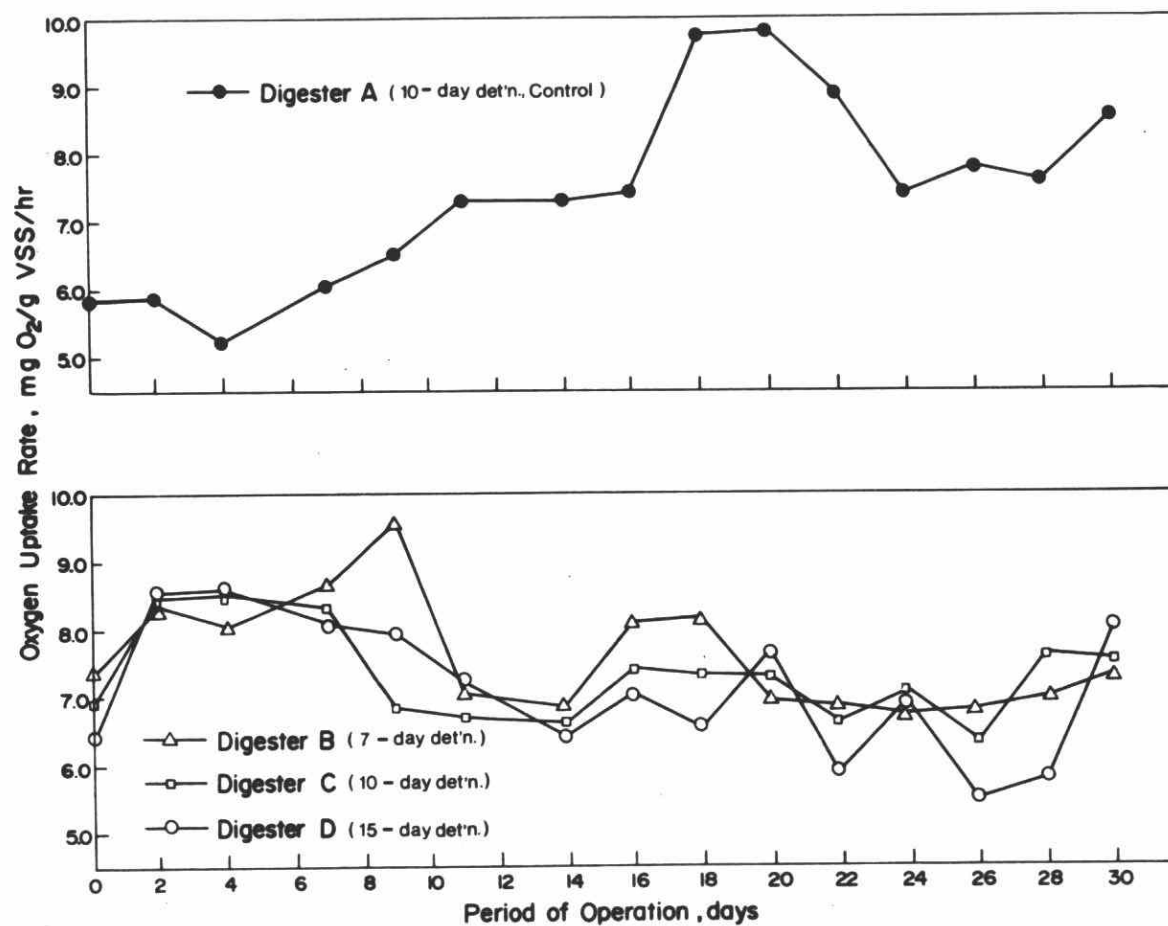
FIGURE 27. DIGESTER OPERATING DATA-OXYGEN UPTAKE RATE AT 20°C (SERIES IV)
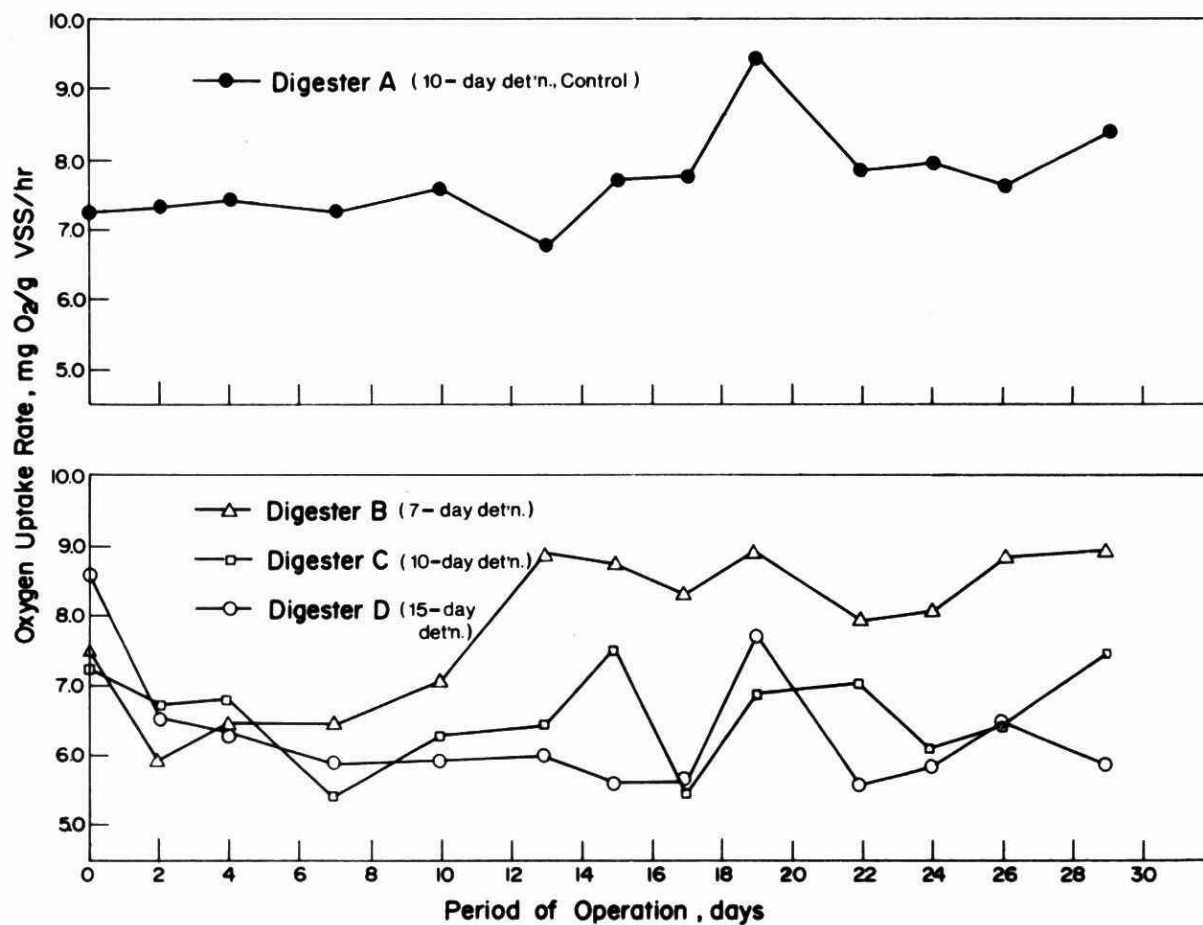
FIGURE 28.   DIGESTER OPERATING DATA—OXYGEN UPTAKE RATE AT 20°C (SERIES Ⅴ)

3.3   Nutrients and Organic Release

        The transformation and release of phosphorus, nitrogen and
organic carbon during aerobic digestion were studied. The results from
the batch and semicontinuous loading experiments are discussed below.

3.3.1   Changes in phosphorus during digestion

        The changes in soluble total phosphorus during aerobic digestion
are shown in Figures 29 and 30 for the Series I and II batch experiments,
respectively. During the first seven days of aeration fluctuations in
the soluble total phosphorus content of the supernatant took place,
after which a distinct trend was observed for each sludge studied. Cell
lysis during endogenous respiration will release phosphorus to the liquid
phase. The released phosphorus will be available for cell synthesis.
Thus, successive release and uptake of phosphorus during the early stages
of aerobic digestion might be the reason for the fluctuations in the
soluble total phosphorus observed in this study. However, as aerobic
digestion progressed, cell lysis accompanying effective endogenous
respiration was more dominant.

        Figures 29 and 30 show that, as the aeration of the primary
(control) sludge A progressed, the sludge released more phosphorus into
the supernatant. The concentration of phosphorus released was substantial
in the Series I experiments, but in the Series II experiments, the
maximum concentration observed during digestion was essentially equal
to the initial concentration in the raw sludge. However, in both series
of the experiments, the primary (control) sludge A showed much more
phosphorus in the liquid phase than any of the lime-primary sludges B,
C, D and E as aerobic digestion progressed. It can also be seen that
no resolubilization of chemically precipitated phosphorus in the lime-
primary sludges occurred during aerobic digestion and that, as digestion
progressed, no practical differences were observed for the soluble
phosphorus content of the supernatants from the different lime-primary
sludges studied.

        Figures 31 to 33 show the supernatant soluble total phosphorus
content for the sludges studied in the semicontinuous loading experiments.
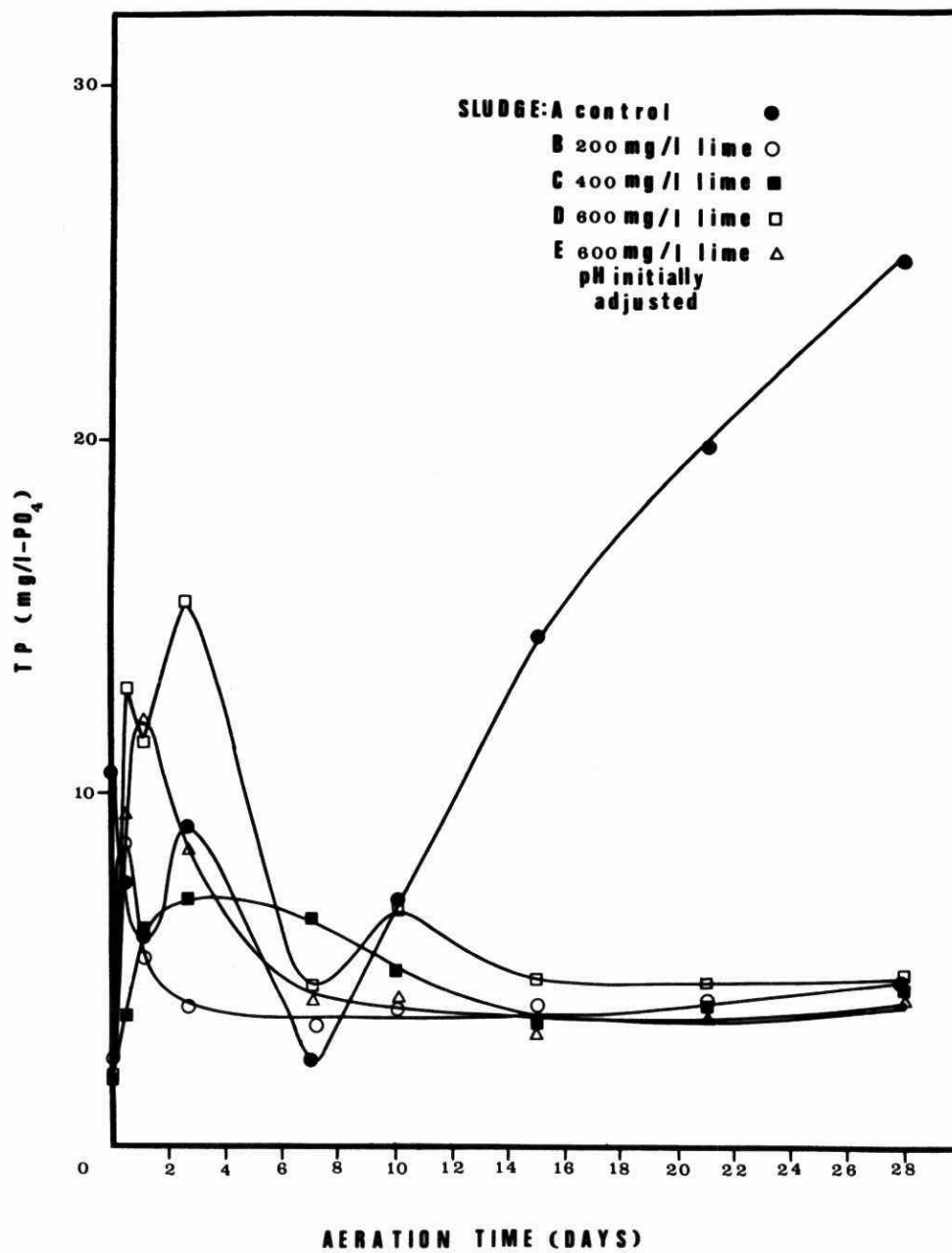All sludges showed essentially low phosphorus in the liquid phase during

48

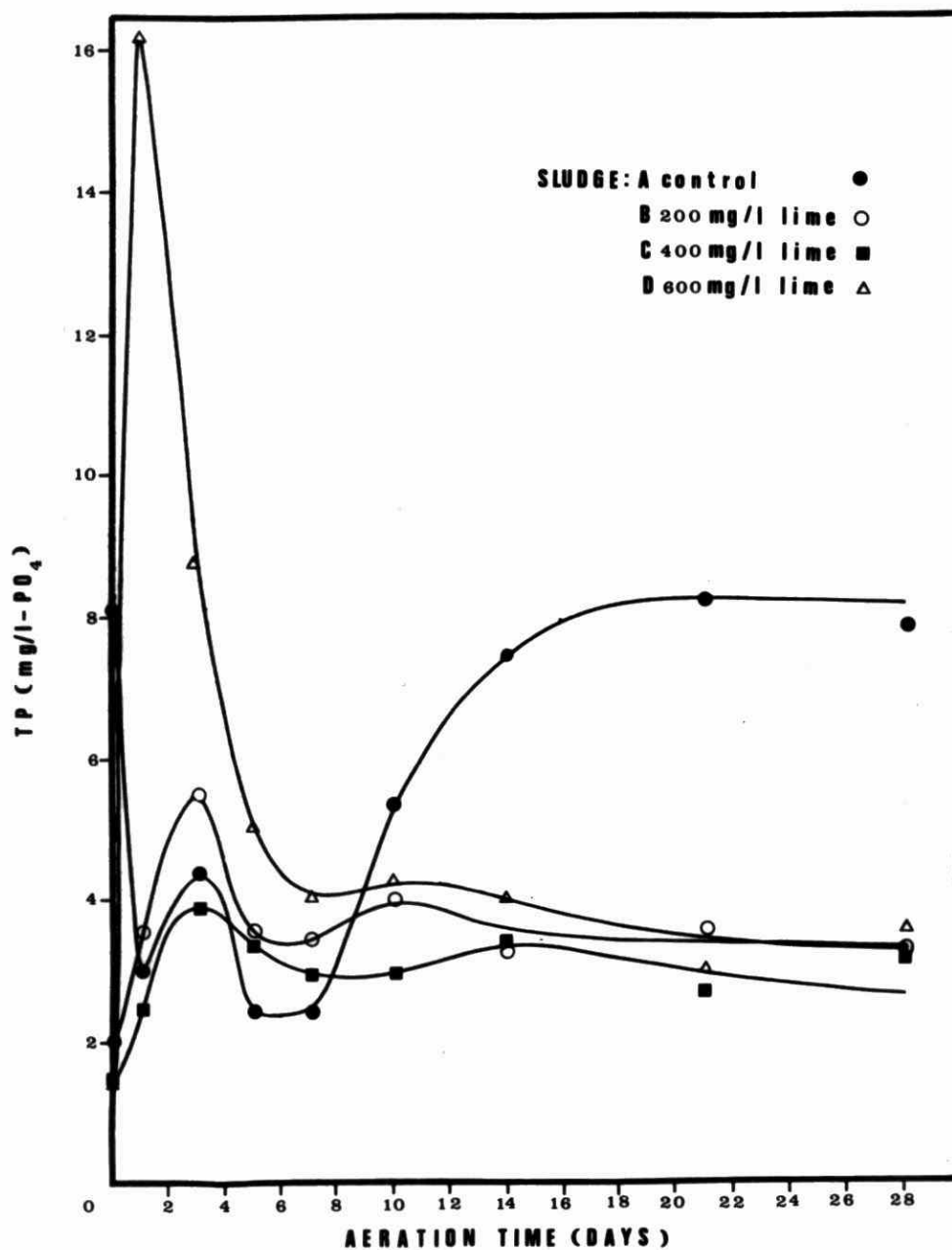FIGURE 29. SOLUBLE TOTAL PHOSPHOROUS (TP) VS AERATION TIME
(SERIES I)

FIGURE 30. SOLUBLE TOTAL PHOSPHOROUS (TP) VS AERATION TIME
(SERIES II)

50

digestion indicating no adverse effect of aerobic digestion. Table 3 presents the soluble total phosphorus concentrations in both the feed and digested sludges for the semicontinuous experiments (Series III, IV and V). Reductions in the soluble phosphorus content of the primary (control) sludges of about 86 to 88 percent were observed as a result of aerobic digestion. For the lime-primary sludges, little change in the soluble phosphorus concentration occurred during aerobic digestion.

The low phosphorus concentrations in the liquid phase during aerobic digestion of the sludges studied indicate that phosphorus was most likely bound to the sludge in the digestion process. It is possible that the process tied up the released phosphorus in the synthesis of new sludge microbial cells. In addition, in the case of the lime-primary sludge, the phosphorus could possibly be chemically bound to the sludge solids.

The supernatants of the digested lime-primary sludges contained slightly higher soluble phosphorus than those of the digested primary (control) sludges. No significant effect of detention time on the changes in soluble phosphorus during digestion was observed, although in Series V, the lime-primary sludge in digester B (seven days detention time) showed a higher soluble phosphorus content than similar sludges in digester C (10 days detention time) and digester D (15 days detention time).

The total phosphorus content of the digested sludge in the semicontinuous loading experiments (Series III, IV and V) at steady state conditions was essentially the same as that of the feed (raw) sludge.

In Series III, IV and V, for the primary (control) sludge, the feed contained less than 4 percent of its total phosphorus in the liquid phase, while, on the average, the digested sludge contained less than 0.6 percent of its total phosphorus in the liquid phase. In contrast, the feed lime-primary sludge contained less than 1 percent of its total phosphorus in the liquid phase while on the average, the digested sludge contained less than 0.8 percent of its total phosphorus in the liquid phase. This demonstrates that, during aerobic digestion, the primary (control) sludge tied up more phosphorus than the lime-primary sludge.

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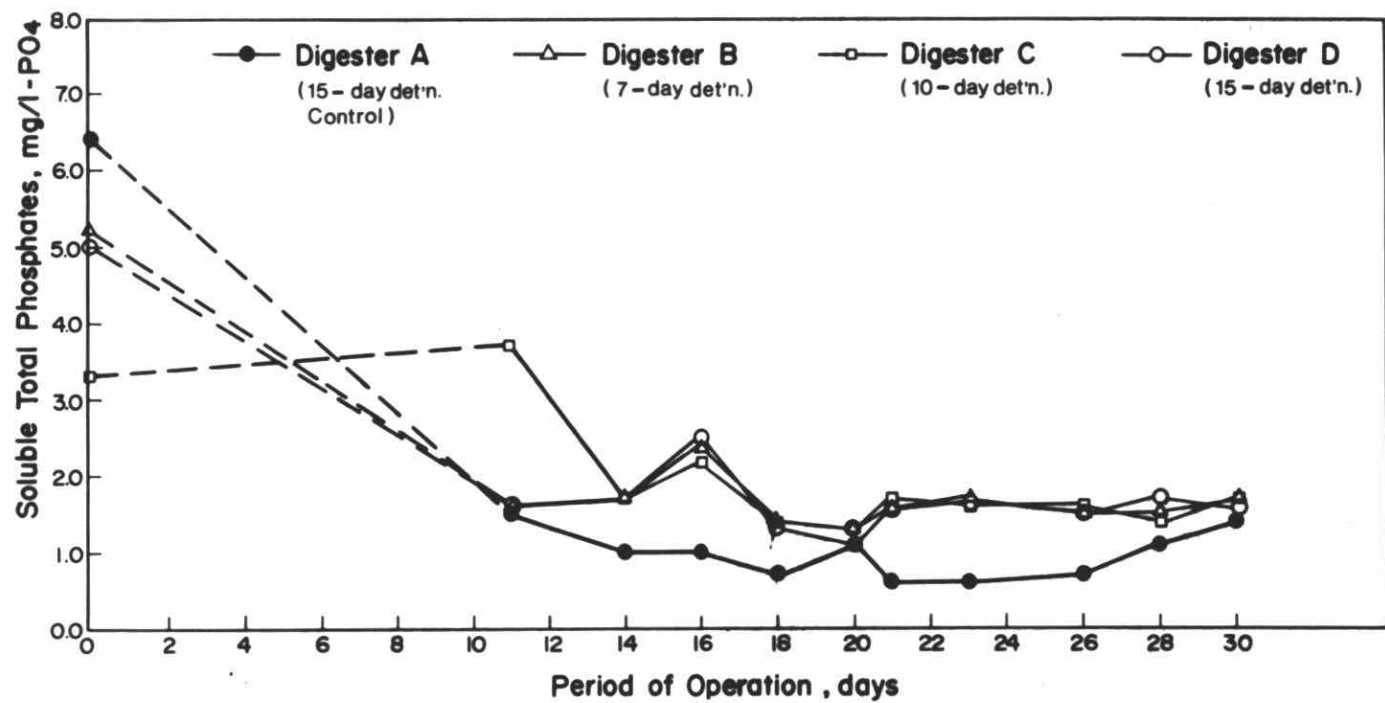
FIGURE 31. DIGESTER OPERATING DATA – SUPERNATANT SOLUBLE TOTAL PHOSPHATE CONTENT (SERIES III)
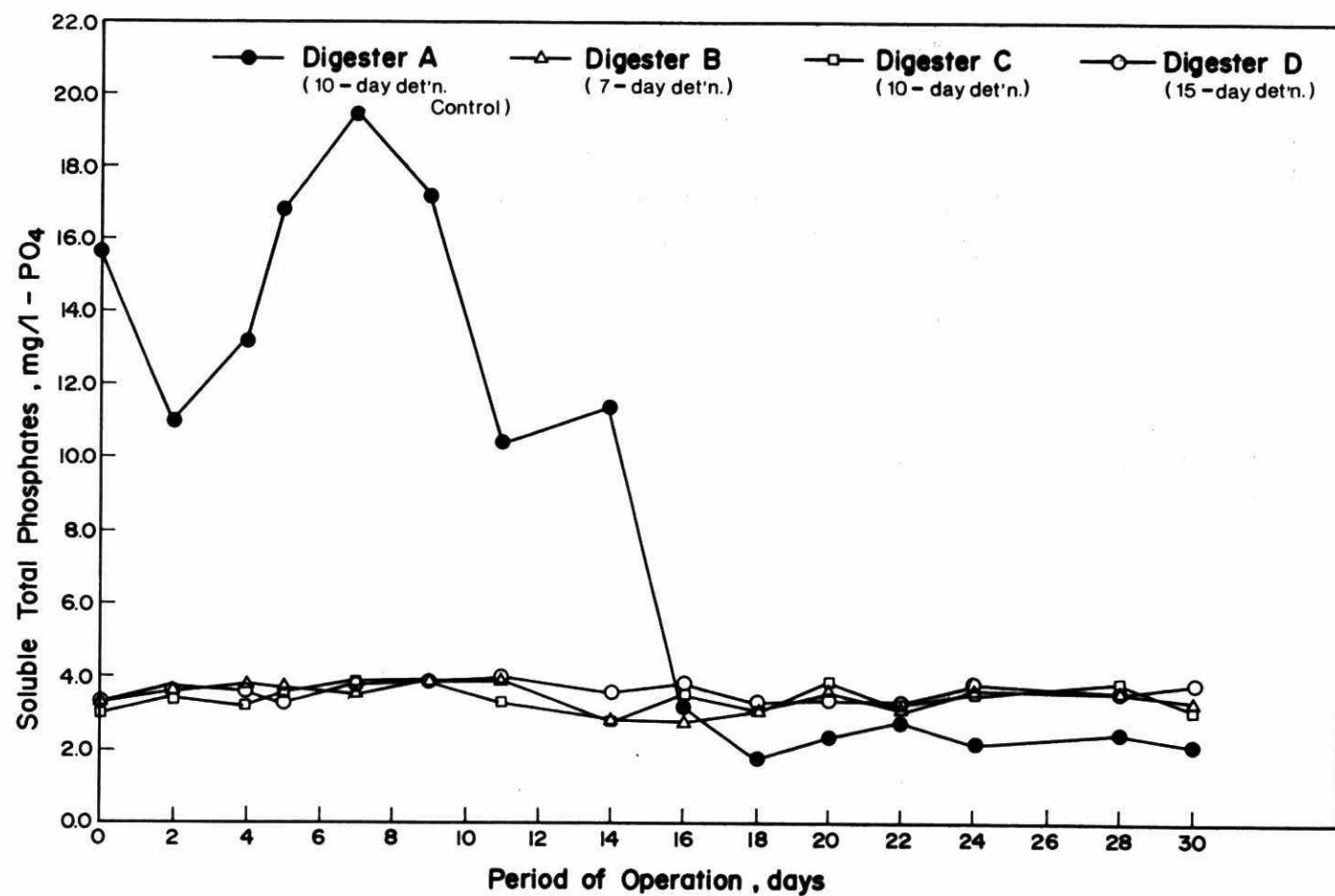
FIGURE 32. DIGESTER OPERATING DATA – SUPERNATANT SOLUBLE TOTAL PHOSPHATE CONTENT (SERIES IV)
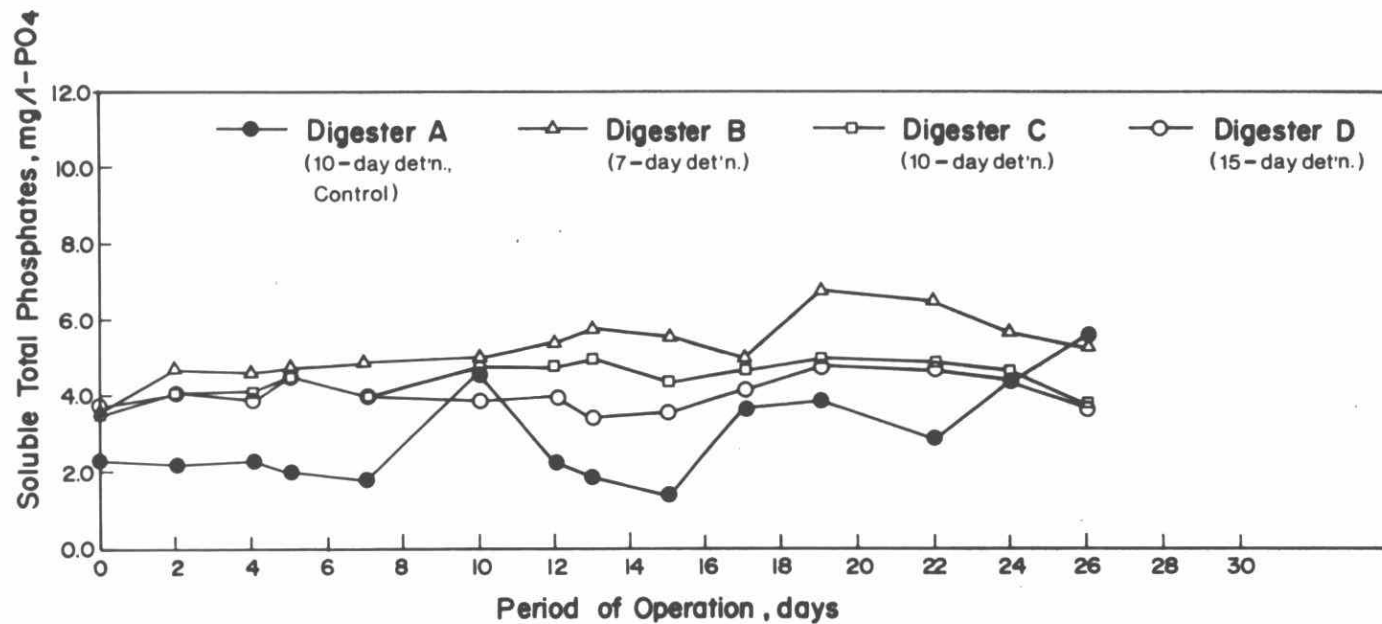
FIGURE 33. DIGESTER OPERATING DATA – SUPERNATANT SOLUBLE TOTAL PHOSPHATE CONTENT (SERIES $\overline{\text{V}}$)

TABLE 3. AVERAGE SOLUBLE TOTAL PHOSPHORUS CONCENTRATIONS IN SLUDGE SUPERNATANT*

Semi Continuous Experiments**	Primary (control) Sludge		Lime-Primary Sludge			
	Feed (mg/1-PO$_4$)	Digested (mg/1-PO$_4$)	Feed (mg/1-PO$_4$)	Digested (mg/1-PO$_4$)		
		Digester A		Digester B	Digester C	Digester D
Series III	8.8	1.0	3.1	1.6	1.6	1.6
Series IV	20.2	2.5	2.7	3.2	3.5	3.5
Series V	26.1	3.7	2.8	5.8	4.6	4.2

*Average values at steady state operation

**See Table 1 for details

Similar observations were made from both the batch loading experiments (Series I and II) and the semicontinuous loading experiments (Series III, IV and V) concerning overall changes in phosphorus during the aerobic digestion of sludges. However, a lower soluble total phosphorus content was observed for primary sludges digested in the semicontinuous loading units than for those digested in batch loading units. A possible explanation is that, in the former digestion units, any released phosphorus will not build up in the system because of the daily discharge of the digested sludge from the system. Also, more phosphorus is expected to be tied up in the synthesis of new sludge cells in the semicontinuous loading units because of the daily addition of raw (feed) sludge substrate.

3.3.2   <u>Nitrogen transformations and release during digestion</u>

The raw (untreated) sludge contains nitrogen in the form of ammonium and organic nitrogen. As given in Table 4, a large portion of the nitrogen (approximately 90%) in the raw sludge was in the form of organic nitrogen and the rest was in the form of ammonium. Only traces of nitrates were found.

TABLE 4.   FORMS OF NITROGEN IN RAW SLUDGE (AVERAGE VALUES)

Series of the Experiments	Primary (control) Sludge			Lime-Primary Sludge		
	TKN^* mg/l-N	NH_4^{**} mg/l-N	NO_3^{***} mg/l-N	TKN mg/l-N	NH_4 mg/l-N	NO_3 mg/l-N
Series I	550	40	0.10	320	20	0.10
Series II	630	82	0.10	280	18	0.10
Series III	476	56.5	0.14	288	19.3	0.90
Series IV	413	56.9	0.13	349	18.5	1.50
Series V	447	65.0	0.17	387	21.1	1.21

*Total Kjeldahl Nitrogen

**Ammonium Nitrogen

***Nitrate Nitrogen

Nitrogen transformations will take place simultaneously during aerobic sludge digestion through several biological processes that change the nitrogen forms. First of all, ammonification will liberate ammonia from organic material. The ammonia liberated, which is the most reduced form of nitrogen, will serve as the starting point for nitrification through which it will be oxidized to nitrites and then to nitrates.

Figures 34 and 35 show the changes in the form of nitrogen with the progress of aeration in the batch loading experiments (Series I and II). The primary (control) sludge A showed a reduction in Kjeldahl nitrogen content with increasing aeration time. In other words, nitrogen was lost from the system during aerobic digestion. The lime-primary sludges B, C, D and E showed essentially no change in Kjeldahl nitrogen content with the progress of aeration. These sludges also had similar Kjeldahl nitrogen contents that were considerably lower than those of the primary (control) sludges.

The ammonia and nitrate data presented in Figures 34 and 35 indicate that, for sludges C, D and E, which were originally precipitated with higher dosages of lime, nitrification was apparently suppressed. Meanwhile, no distinct differences were observed in the release of ammonia from the sludges studied. The concentrations of ammonia observed were generally low.

In the semicontinuous loading experiments (Series III, IV and V) the ammonium nitrogen content of the supernatant in all digesters, at steady state conditions, was generally below 1 mg/l, although in a very few cases slightly higher concentrations were found (digesters B, C and D in Series IV). Three different factors could have contributed to the low concentration of ammonium observed. These factors are the nitrification of ammonia to nitrites and nitrates, the stripping of ammonia gas and/or the utilization of ammonia released in synthesis of new sludge microbial cells.

Nitrification was only significant in digester A treating primary (control) sludges and in digester D treating lime-primary sludges at a detention time of 15 days; the rate of nitrification was much more appreciable in digester A. This indicates that nitrification
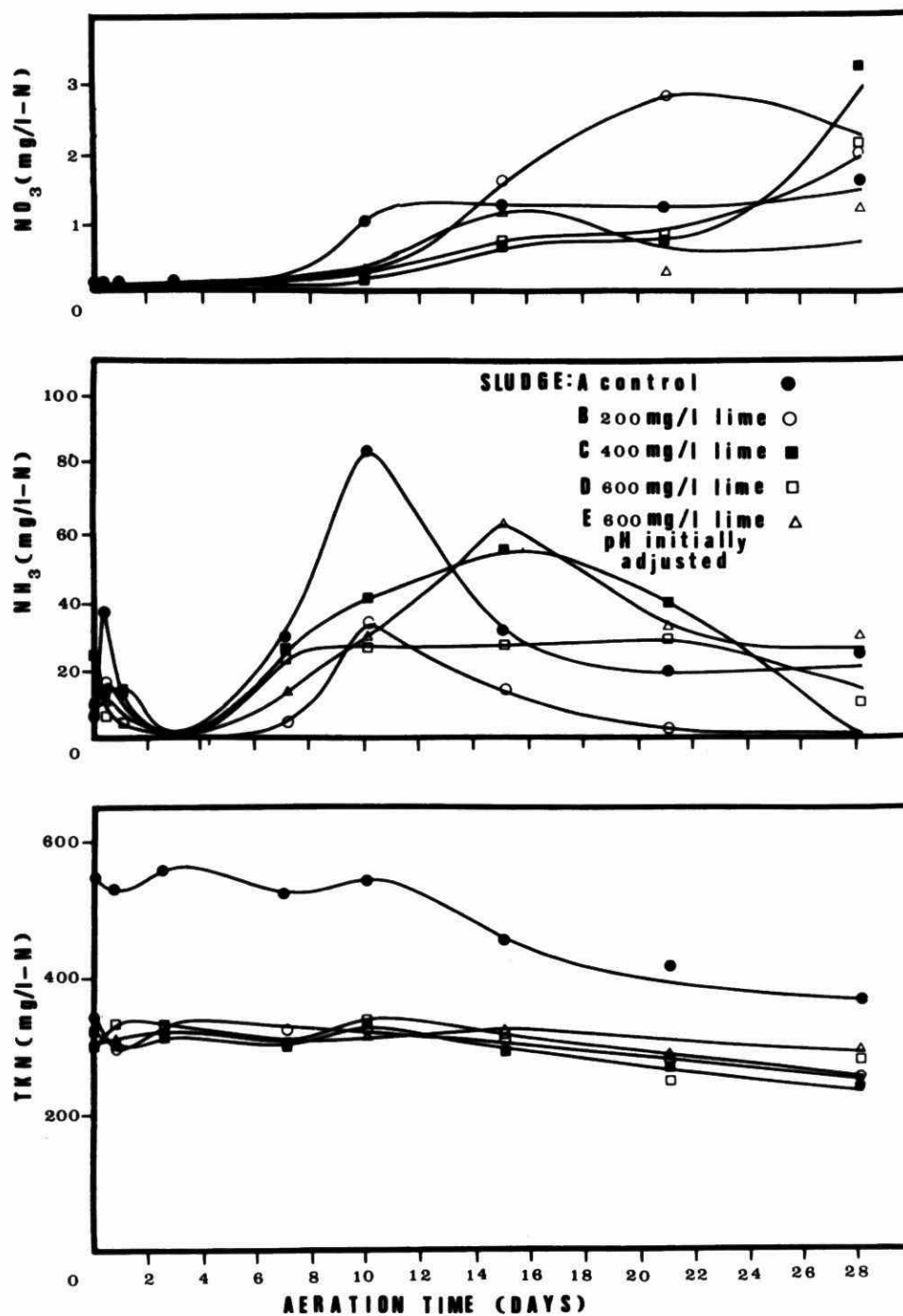
57

FIGURE 34. NITRATE(NO₃), AMMONIA NITROGEN(NH₃)(SUPERNATANT) AND TOTAL KJELDAHL NITROGEN (TKN)(SLUDGE)VS AERATION TIME (SERIES I)
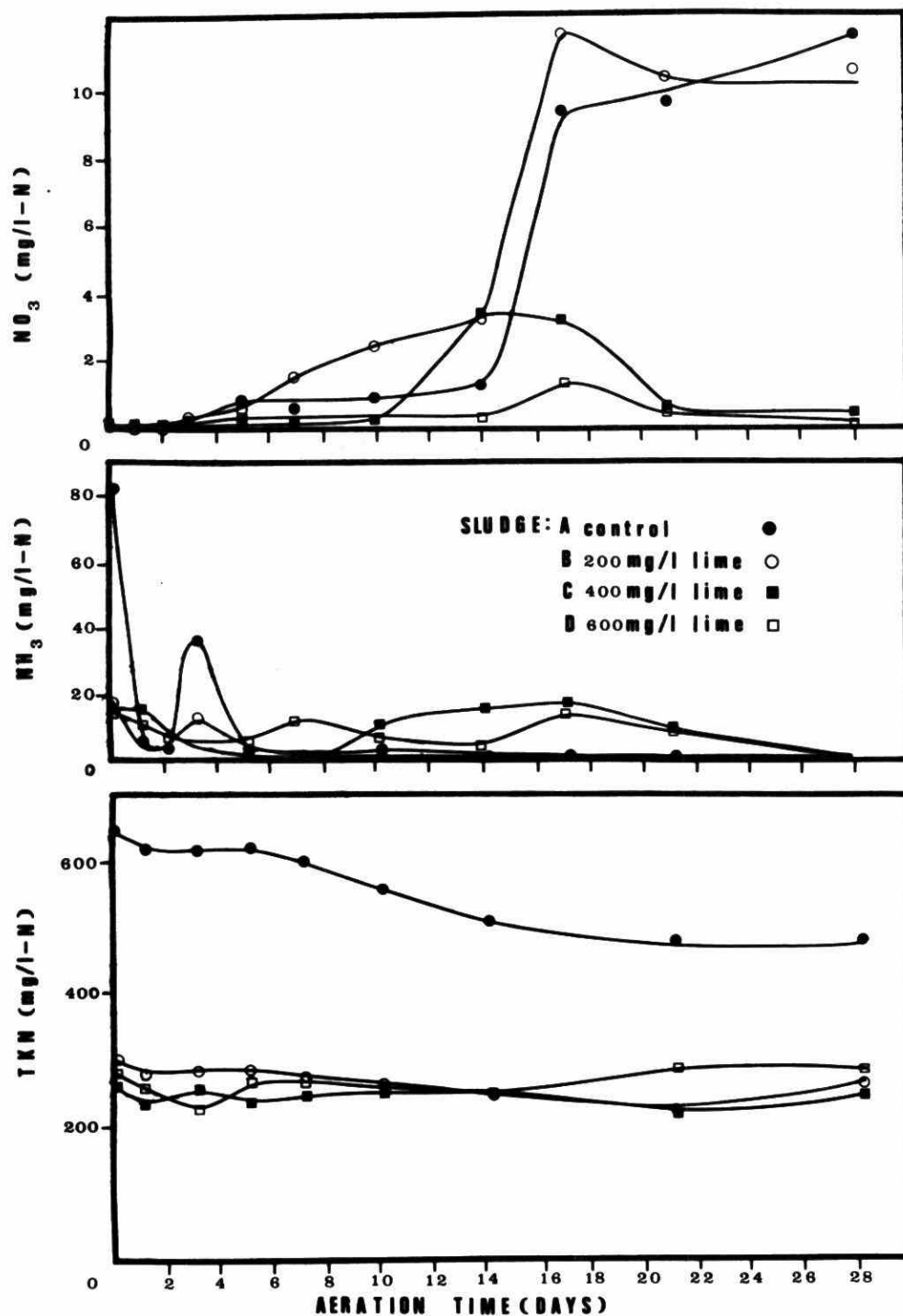
58

FIGURE 35. NITRATE(NO$_3$), AMMONIA NITROGEN(NH$_3$)(SUPERNATANT)AND
TOTAL KJELDAHL NITROGEN(TKN)(SLUDGE) VS AERATION TIME
(SERIES II)

was delayed and did not progress efficiently in the digesters treating lime-primary sludges. The concentration of nitrites in the digesters was checked frequently and found to be very low (traces).

The second factor is the ammonia stripping from digesters which is possible at high pH. This was checked in each digester by sealing the digester and allowing the exhausted air from the digester to pass through a boric acid solution in order to entrap any ammonia that might be stripped from the digester. The air used for aeration in this case was freed from ammonia before entering the digester. The ammonia entrapped in boric acid was measured. Ammonia stripping from digesters treating lime-primary sludge was observed but was not significant.

The third factor that could have contributed to the low ammonia concentrations observed is that ammonia released during the decomposition of organic solids might have been tied up in the synthesis of new microbial cells. This is expected with primary sludges especially in the semicontinuous loading system where raw sludge is fed daily to the system. It is believed that the latter factor is the most significant.

As in the Series I and II experiments, no practical change in the Kjeldahl nitrogen content of the lime-primary sludges was observed as a result of the aerobic digestion in the Series III, IV and V experiments. However, in all these experiments, the Kjeldahl nitrogen content of the sludges as a percentage of volatile suspended solids in the lime-primary sludge increased with increasing digestion time. This would indicate that the sludge solids were synthesizing more nitrogen-containing material. The latter explanation supports the belief that ammonia released during aerobic digestion is tied up in the synthesis of new microbial protoplasm.

3.3.3   Organic carbon release

The soluble total organic carbon and the soluble chemical oxygen demand of the sludge supernatant were measured. Figures 36 and 37 show that, in the batch loading experiments (Series I and II), soluble TOC and COD rapidly decreased during the first five days of aeration and later on remained essentially constant, although on about the tenth day of aeration, some small increases occurred in Series II. Since no
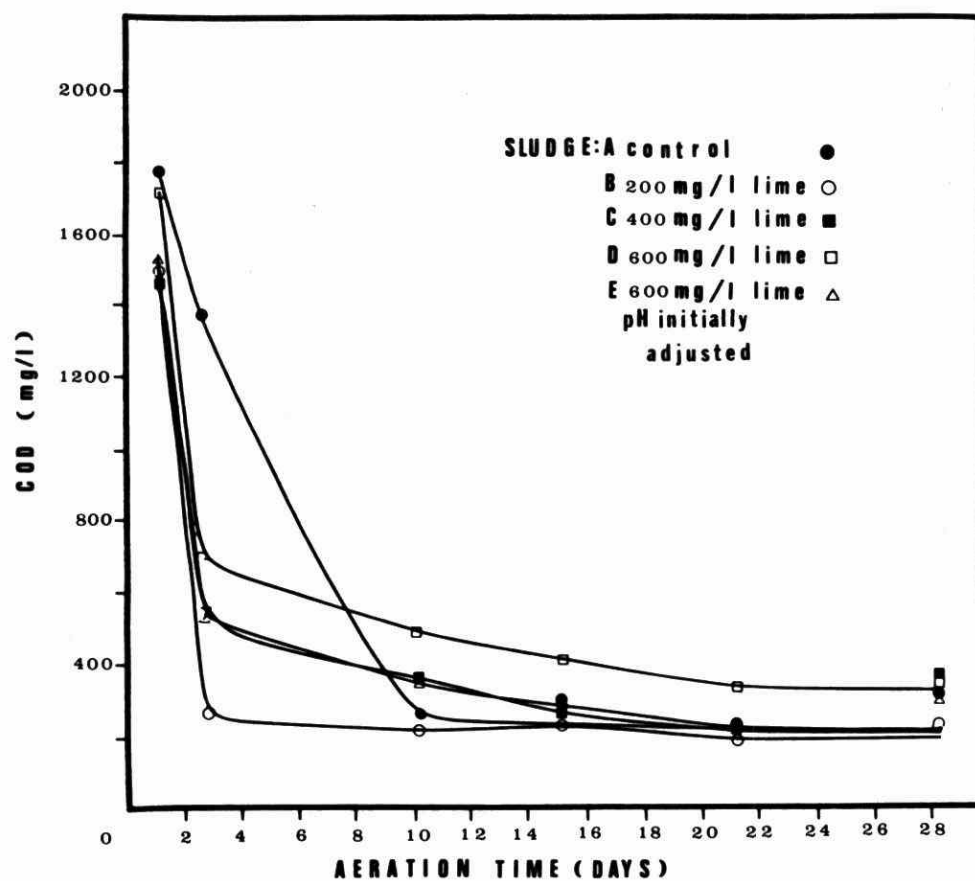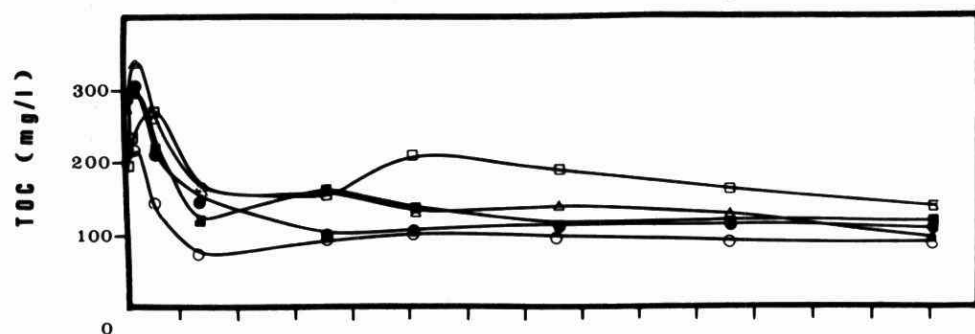
60

FIGURE 36. CHANGES IN SOLUBLE TOTAL ORGANIC CARBON(TOC) AND
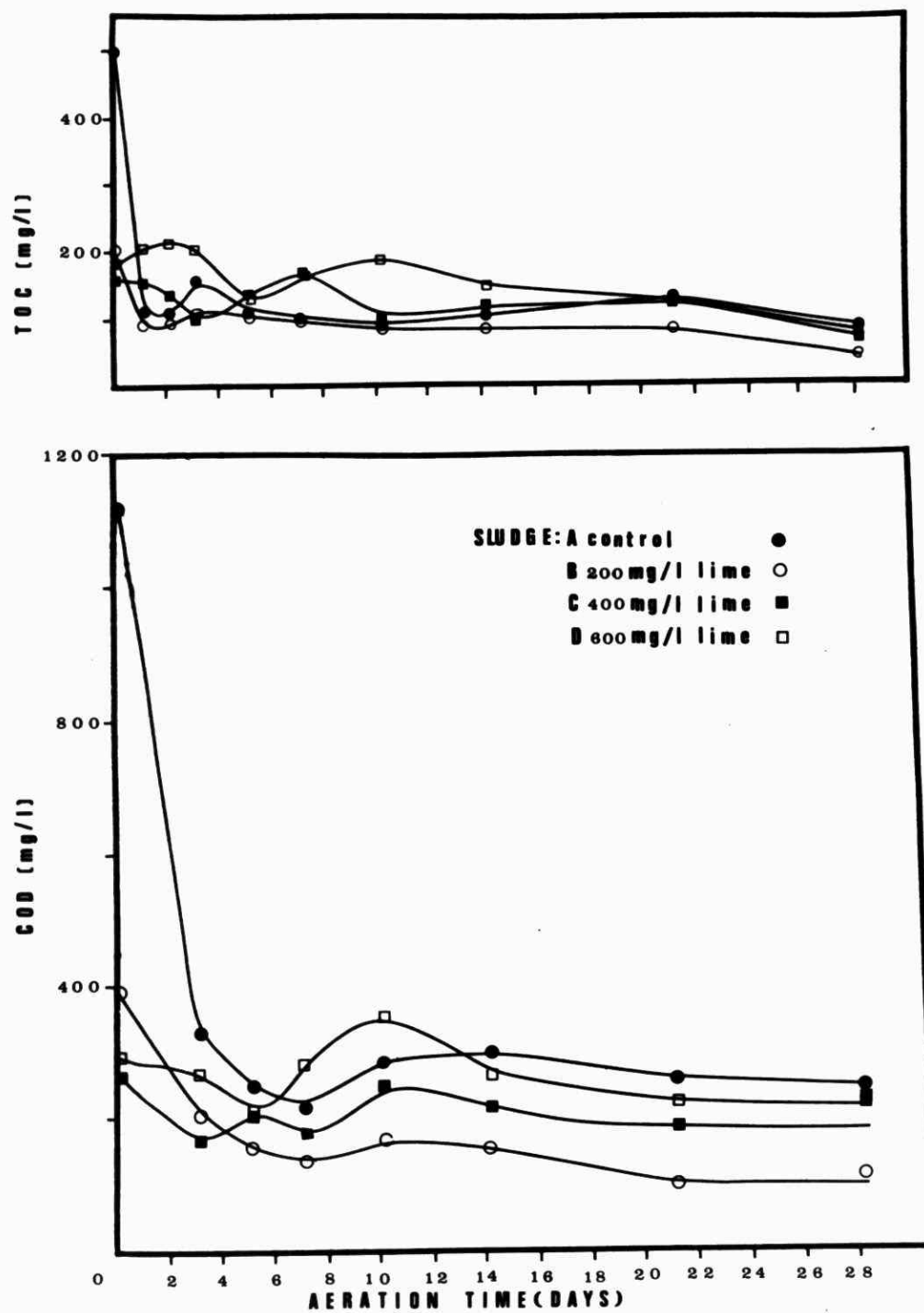SOLUBLE CHEMICAL OXYGEN DEMAND(COD) (SERIES I)

FIGURE 37. CHANGES IN SOLUBLE TOTAL ORGANIC CARBON(TOC)AND
SOLUBLE CHEMICAL OXYGEN DEMAND(COD) (SERIES II)

obvious release of organic carbon was observed, it is thought that the material released by cell lysis as a result of endogenous respiration was available for uptake by other microbial cells.

Figures 38 to 40 show the operating data on soluble COD and TOC in the semicontinuous loading experiments (Series III, IV and V). These figures generally show that the soluble COD and TOC concentrations were essentially constant once the steady-state conditions were established. The soluble COD and TOC concentrations were generally low and were not different for the different lime-primary sludges studied in Series III, IV and V. On the average, the values reported for these sludges were between 100 to 120 mg/l soluble COD.

No significant effect of detention time on soluble COD concentrations was observed in digesters B, C and D (Figures 38 to 40). The primary (control) sludge in digester A showed no general trend as the concentration of soluble COD was similar to, higher than, and lower than the lime-primary sludges in Series III, IV and V, respectively. The average soluble COD concentrations observed for the primary (control) sludge in digester A were 110, 160 and 85 mg/l for Series III, IV and V, respectively. The corresponding detention times in digester A were 15, 10 and 10 days, respectively. It is believed that the difference in the soluble COD concentrations in the feed primary (control) sludges studied in these various series of experiments was the primary reason.

The ratio of soluble TOC to soluble COD was generally lower for the digested primary (control) sludge than for the digested lime-primary sludges studied in Series IV and V. The supernatant of the digested lime-primary sludge contained a soluble TOC of about 40% of the soluble COD value whereas that of the digested primary (control) sludge contained a soluble TOC of about 32% of the soluble COD value. This indicates a greater potential nutritional value for the supernatant of the digested lime-primary sludges.

The comparison between the results from the batch loading experiments and the semicontinuous loading experiments regarding the organic carbon content of the supernatants from sludges digested in both systems indicate that the latter system produces supernatants with lower organic carbon content. As is the case for other nutrients (phosphorus
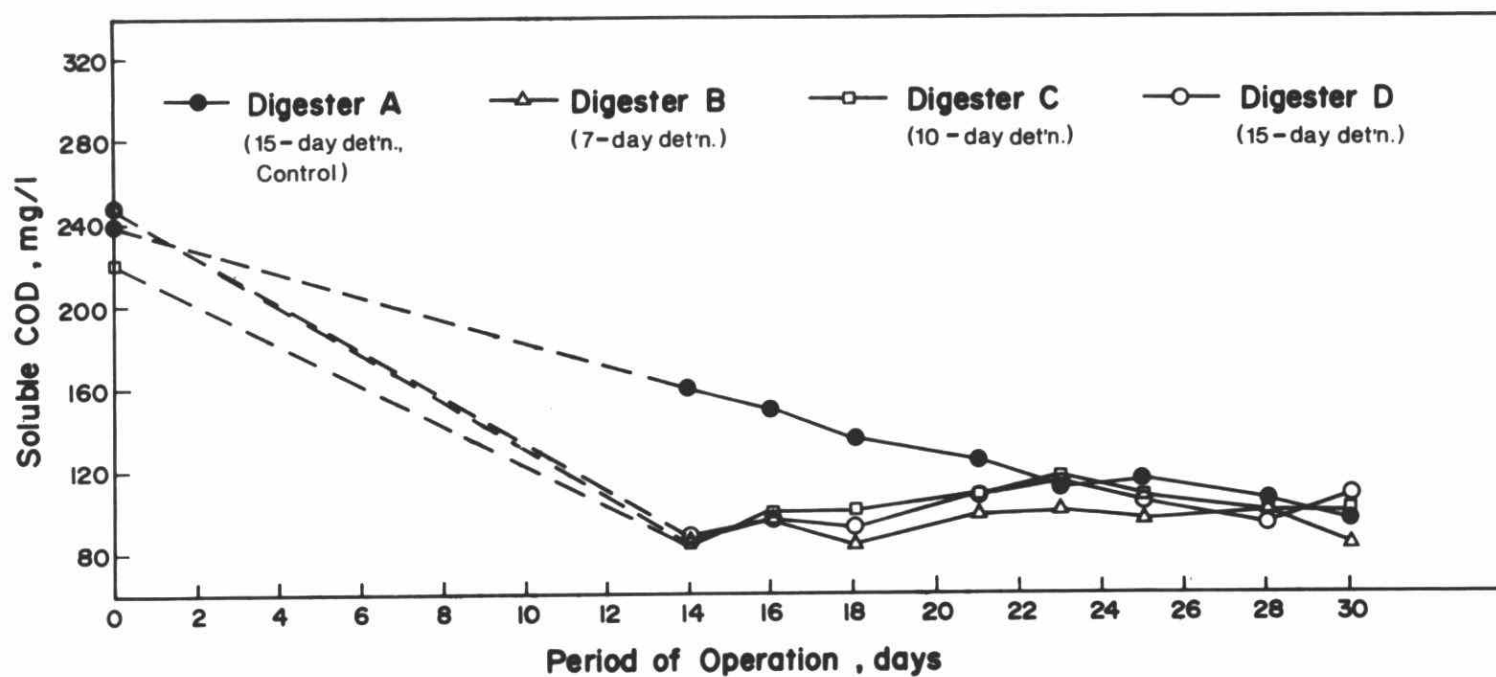
63

FIGURE 38. DIGESTER OPERATING DATA – SUPERNATANT SOLUBLE CHEMICAL OXYGEN DEMAND (COD) (SERIES Ⅲ)
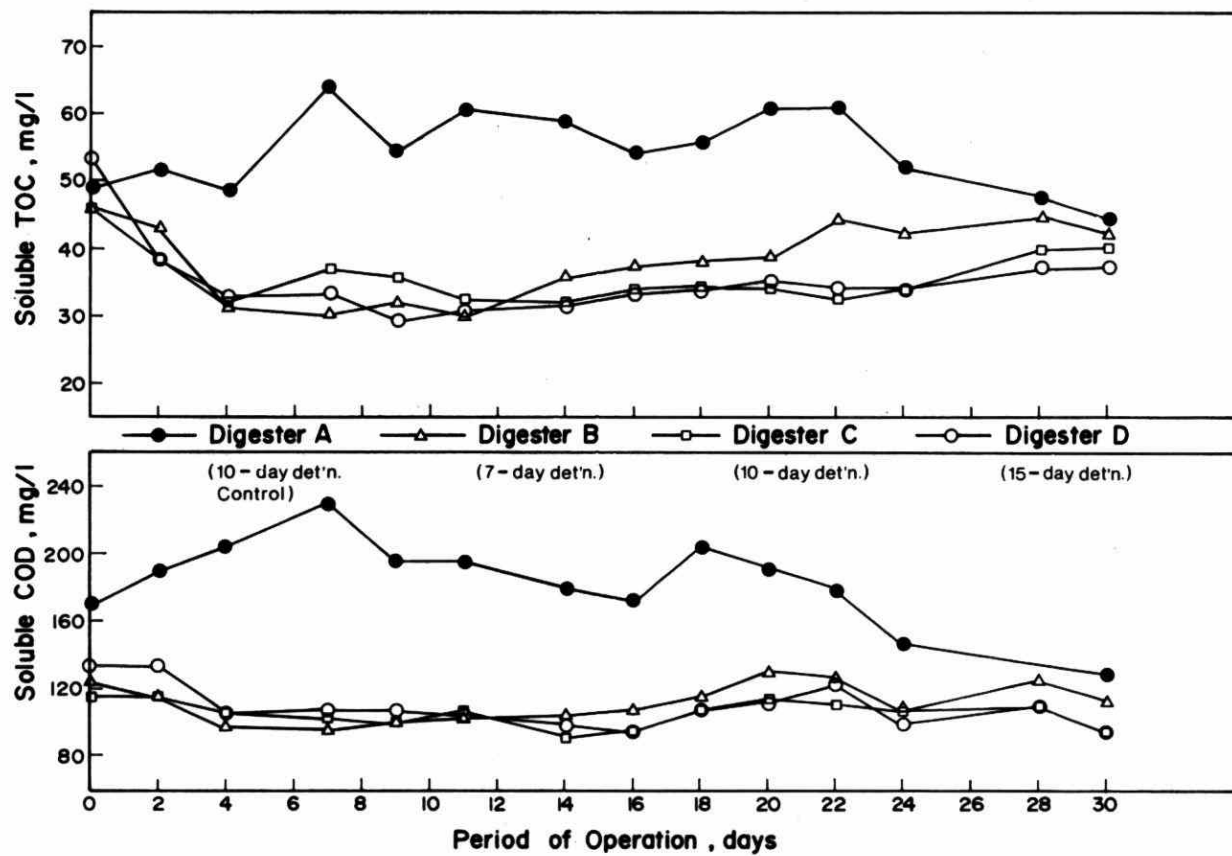
64

FIGURE 39. DIGESTER OPERATING DATA — SUPERNATANT SOLUBLE CHEMICAL OXYGEN DEMAND (COD) AND SOLUBLE TOTAL ORGANIC CARBON (TOC) (SERIES IV)
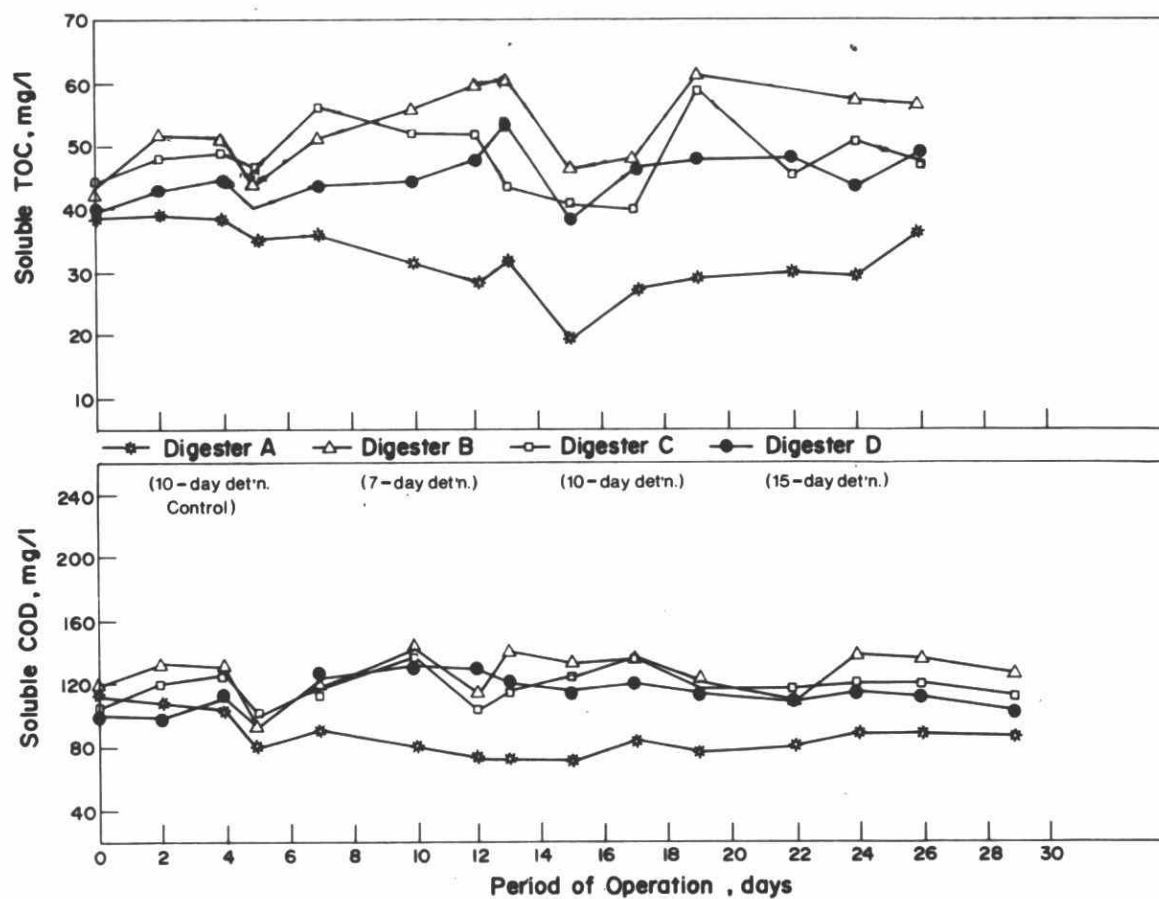
FIGURE 40.   DIGESTER OPERATING DATA – SUPERNATANT SOLUBLE CHEMICAL OXYGEN DEMAND (COD)
AND SOLUBLE TOTAL ORGANIC CARBON (TOC)
(SERIES Ⅴ)

and nitrogen), the lower organic carbon content of the supernatants from sludges digested in semicontinuous loading systems is the result of the daily discharge of the digestion products accompanied by the daily addition of fresh (raw) sludge feed practised in such systems. This creates conditions of minimal build-up of digestion products and higher potential for use of some released material by the sludge microbial cells.

3.4 . Flocculent Nature and Dewaterability of Sludges

The flocculent nature of the sludges during aerobic digestion was studied by the measurement of the suspended solids in the supernatant after settling for two hours in a one-litre graduated cylinder. The settling characteristics and filterability of the sludges were also studied. Laboratory settling and vacuum filtration tests were described in a previous report (Ganczarczyk and Hamoda, 1973).

It should be noted that the mixing conditions in digesters could affect the settling and filtration characteristics of the digested sludge. Efforts were made to ensure uniform mixing conditions in all digesters during aerobic digestion experiments.

The data on supernatant suspended solids for the Series II batch loading experiments are presented in Figure 41. The lime-primary sludges precipitated with higher dosages of lime (sludges C and D) showed a higher degree of dispersion during the aerobic digestion than the primary (control) sludge A. However, sludge B (precipitated with 200 mg/l lime) produced a supernatant much clearer than that of the control sludge A. The supernatant of sludge B, unlike those of other sludges studied, showed only a slight deterioration (as measured by suspended solids content) with the progress of aeration.

In the semicontinuous loading experiments (Series III, IV and V) the digested sludges produced supernatants that possessed considerably lower suspended solids content than those from digested sludges in the batch loading experiments (Series II) shown in Figure 41. In Series III, IV and V the supernatant of the digested primary (control) sludge contained higher suspended solids than the supernatants of the digested lime-primary sludges. Among the latter, there was no distinct difference between the digested sludges from Series III, IV and V concerning the
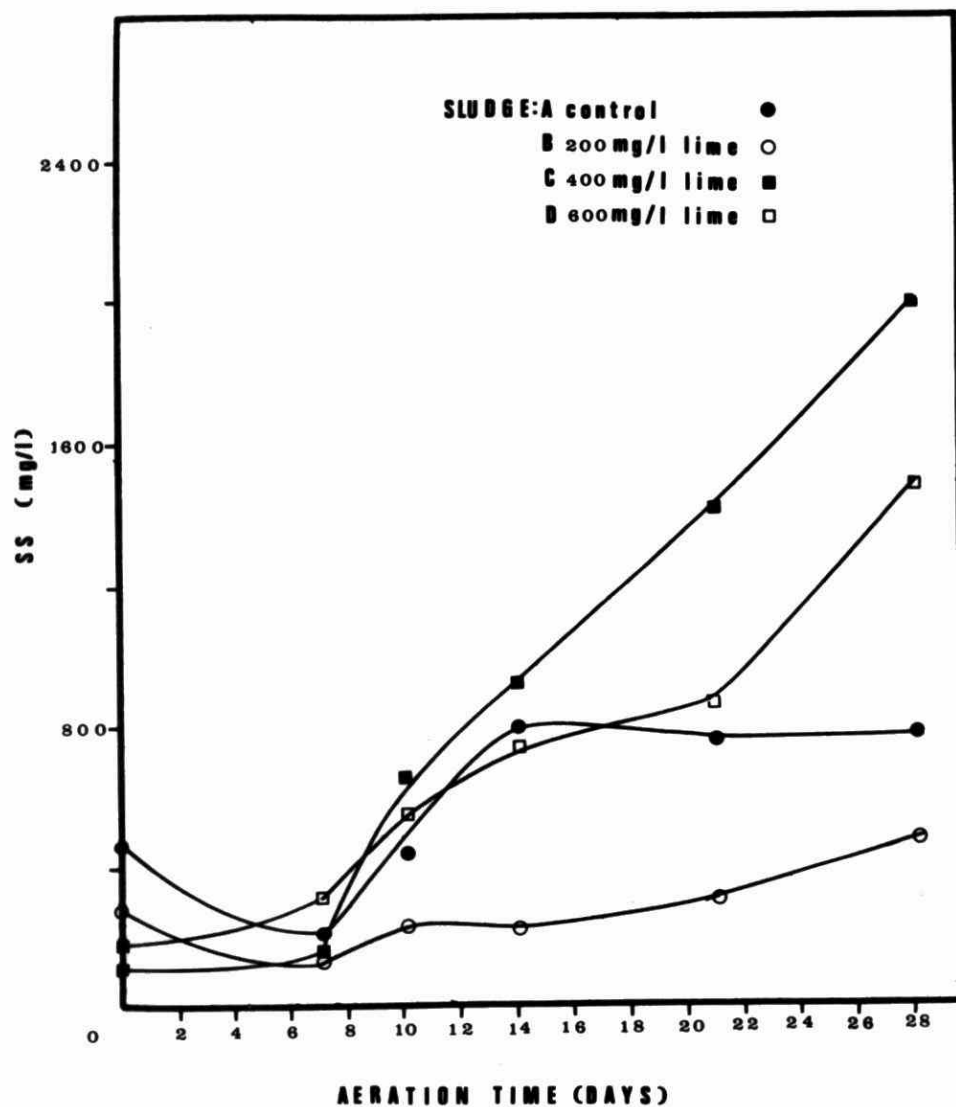
67

FIGURE 41.   SUPERNATANT SUSPENDED SOLIDS (SS)
VS AERATION TIME
(SERIES II)

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suspended solids content of the supernatant. However, the detention time in the digester had a more distinct effect on the suspended solids content of the digested sludge supernatant. The lime-primary sludges from digester B (seven-day detention time) produced supernatant that contained less suspended solids than those produced from any of the lime-primary sludges from digester C (10-day detention time) or digester D (15-day detention time). The latter digesters (C and D) were similar in this respect.

The average suspended solids content of the supernatants from the feed (untreated) primary sludges (control) was 502 mg/l and was reduced to 117 mg/l in digested sludge from digester A of Series III (15-day detention time) and to 125 mg/l from digester A of Series IV and V (10-day detention time). In contrast, the average suspended solids content of the supernatants from the feed (untreated) lime-primary sludges studied in Series III, IV and V were 190, 60 and 38 mg/l, respectively. The average suspended solids concentrations found in the supernatants from digester B were 75, 79 and 82 mg/l, respectively. The corresponding average values in digester C were 93, 95 and 96 mg/l, respectively, and in digester D were 100, 100 and 96 mg/l, respectively.

The feed lime-primary sludges studied in Series IV and V had lower supernatant suspended solids than sludges studied in Series III. However, similar values for the supernatant suspended solids were observed for any of the digested lime-primary sludges from a particular digester regardless of the suspended solids content of the supernatant of the feed sludge used. Thus, the supernatants from the sludges studied in Series IV and V (sludges precipitated with high lime doses) showed comparatively more deterioration in suspended solids during aerobic digestion. This is in agreement with findings from the Series II batch loading experiments for sludges C and D that resemble the sludges studied in Series IV and V, respectively.

Laboratory settling tests on the sludges studied in the Series II batch experiments showed that sludge B (precipitated with 200 mg/l lime) settled more rapidly than any of the sludges A, C and D. The aerobic digestion of the lime-primary sludges B, C and D markedly

improved their settleability whereas the settleability of sludge A
(control) was only slightly improved by aerobic digestion.

The settling characteristics of feed and digested sludges in
the semicontinuous loading experiments (Series III, IV and V) were invest-
igated. Results from laboratory settling tests were evaluated. An
example is shown in Figure 42 for a settling curve and the determination
of the interface velocity (V_i). The latter was used to compare the
settling characteristics of the sludges studied while taking into
consideration the different solids concentration of these sludges. The
evaluation of data from laboratory settling tests revealed that, in
Series III, IV and V, aerobic digestion improved the settling character-
istics of primary (control) sludges and lime-primary sludges. The
improvement for the latter was more appreciable.

Vacuum filtration tests were conducted on feed and digested
sludges. Tests on sludges studied in the Series II batch loading
experiments generally showed that the lime-primary sludges possessed
considerably better dewatering characteristics than conventional
primary sludges (control). The addition of higher dosages of lime to
raw sewage resulted in sludges with initially better filterability.
Aerobic digestion of sludge B (precipitated with 200 mg/l lime) significant-
ly improved its filterability to such a degree that, with the progress
of aeration, the filterability of sludge B was similar to or even better
than that of sludge C or D (precipitated with 400 mg/l and 600 mg/l lime,
respectively) at similar aeration times. The filterability of digested
sludge B was far superior to that of sludge A (control primary sludge)
at similar aeration times.

The aerobic digestion of sludge A initially improved its
filterability but later on (after seven days of aeration), the
filterability decreased with the increase in aeration time. Meanwhile,
the progressive aeration of sludges C and D resulted in the deterioration
of their filtration properties.

In the semicontinuous loading experiments (Series III, IV and
V), the filterabilities of the different sludges were compared in terms
of the sludge's specific resistance to filtration. The data from a
vacuum filtration test on the sludge were plotted as shown in Figure 43.
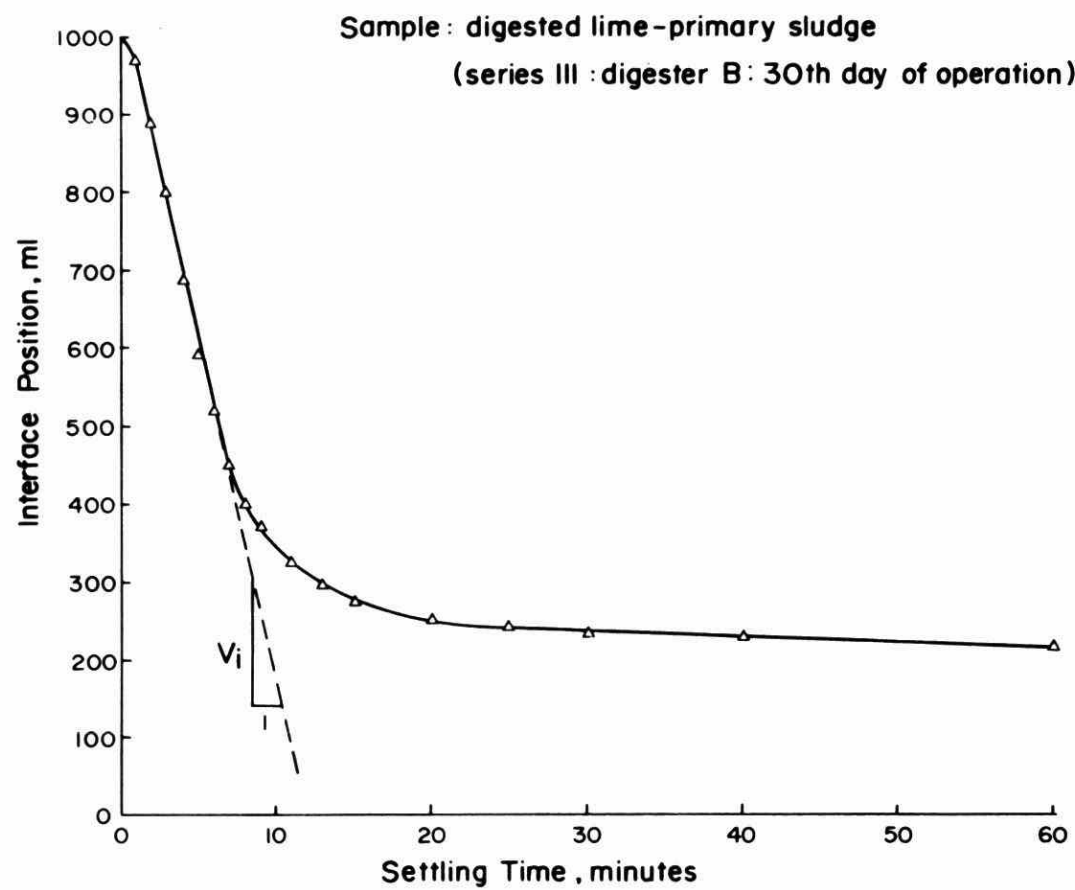
70

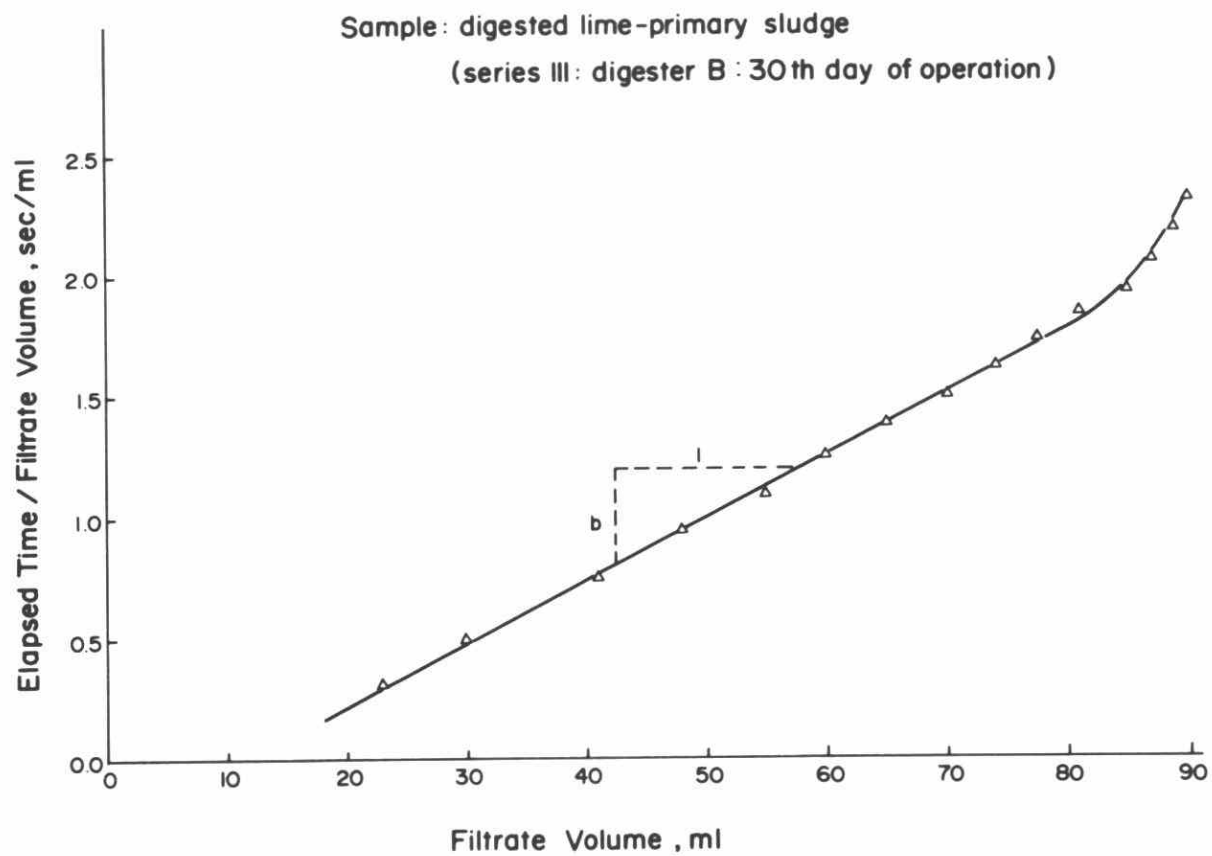FIGURE 42.   SLUDGE SETTLING CURVE (An Example)

FIGURE 43.   PLOT OF ELAPSED TIME / FILTRATE VOLUME VS. FILTRATE VOLUME TO DETERMINE b (An Example)

The slope b was determined and later used to estimate the specific resistance of the sludge from the following relationship (Culp and Culp, 1971):

$$r = \frac{2 \, b \, P \, A^2}{\mu c}$$

where: b = slope of $\dfrac{\text{time}}{\text{filtrate volume}}$ vs filtrate volume (sec/cm^6)

P = applied vacuum (g/cm^2)

A = area of filtering surface (cm^2)

μ = filtrate viscosity (poises)

c = weight of solids/unit volume of sludge prior to filtration (g/ml)

r = specific resistance (sec^2/g).

In vacuum filtration tests conducted in this study the following values were used:

P = 15 in. Hg = 526 g/cm^2

A = 38.48 cm^2 (Whatman Filter Paper #1, diam. = 7 cm)

μ = 1.0087 x 10^{-2} poises (at $20^{\circ}C$).

The following table (Table 5) presents the average values of specific resistance found for different sludges studied.

The results of the filterability of the feed (untreated) sludges studied in Series III, IV and V (as given in Table 5) indicate that the lime-primary sludges possessed considerably better filterability (lower specific resistance) than the primary (control) sludge. For the digested sludges, it was observed that the filterability of the primary (control) sludge significantly improved as a result of aerobic digestion. The filterability of the lime-primary sludges was also improved except in the Series V experiments where a slight deterioration in filterability occurred as a result of aerobic digestion.

The effect of detention time in the digester on the filterability of the digested sludges was observed. Longer detention times in the digesters generally resulted in a decrease of digested sludge filterability.

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TABLE 5. AVERAGE VALUES OF SPECIFIC RESISTANCE TO FILTRATION

| Series of Semi-Continuous Loading Experiments* | Primary (control) Sludge | | Lime-Primary Sludge | | | |
	Feed (sec^2/g)	Digested Digester A (sec^2/g)	Feed (sec^2/g)	Digested Digester B (sec^2/g)	Digester C (sec^2/g)	Digester D (sec^2/g)
Series III	1375×10^7	180.50×10^7	64.25×10^7	20.75×10^7	32.92×10^7	59.83×10^7
Series IV	1106×10^7	182.50×10^7	27.30×10^7	11.83×10^7	10.88×10^7	17.03×10^7
Series V	1039×10^7	139.01×10^7	11.82×10^7	16.04×10^7	24.03×10^7	23.83×10^7

*See Table 1 for details

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4.   COMPARISON AND APPLICABILITY OF RESULTS OF PHASE I AND II

In Phase I of the study (Ganczarczyk and Hamoda, 1973), aerobic digestion of waste activated sludges precipitated with alum (8.1-22.3 mg/l as Al^{+3}) or ferric chloride (10-30 mg/l as Fe^{+3}) was studied. The present investigation, Phase II of the study, examined the aerobic digestion of primary sludges precipitated with lime (140-600 mg/l). The range of chemical dosages studied are those commonly used in waste-water treatment practice. For comparative purposes, all sludges studied had essentially similar initial volatile solids content. Although the characteristics of the substrate in the waste activated sludge and the primary sludge are basically different, the use of control sludges (no chemical addition) in each of Phase I and Phase II experiments made it possible to examine generally the effect of chemicals on the behaviour of sludges during aerobic digestion in each case.

The results from Phases I and II of the study show that aerobic digestion of sewage sludges is practically not inhibited by the presence of aluminum, iron, or calcium and their precipitates in the sludge in the range of chemical dosages studied. However, at high lime dosages, the digestion process kinetics is adversely affected. The release of soluble organics and mineral nutrients (phosphorus and nitrogen) by cell lysis or the uptake of these materials for cell synthesis that occur during aerobic digestion are not enhanced in the presence of the chemicals studied. Nitrification that accompanies aerobic digestion is not inhibited normally by the presence of aluminum or iron and their precipitates in the sludge but the presence of calcium and its precipitates may inhibit the nitrification process when lime dosages in excess of 200 mg/l are used. The dewatering characteristics of the aerobically digested sludges containing iron precipitates are generally better than those of sludges containing aluminum precipitates but are inferior to those of sludges containing calcium precipitates.

On the basis of overall performance of the aerobic sludge digestion process, it may be concluded that ferric chloride, alum, and lime can be selected in this order for better performance. However, in full scale operation of aerobic digesters, the problems associated with different chemicals such as mixing, corrosion and scaling problems must be considered.

The study also showed that the type of sludge (primary or waste activated sludge) and the mode of operation of the digester (batch or semicontinuous) are important factors affecting the behaviour of the sludge during aerobic digestion.

The results indicate that aerobic digestion of primary sludge or waste activated sludge is equally effective from a practical stand-point but the changes occurring during aerobic digestion of these two types of sludges are somewhat different. The release of organics, phosphorus, and nitrogen during aerobic digestion of waste activated sludge is not apparent in the case of primary sludge, probably due to subsequent uptake of released material in the latter case. It is also interesting to note that aerobic digestion considerably improves the dewatering characteristics of the primary sludge, while it may not do so for the waste activated sludge.

As for the mode of operation of the digester, the study revealed that the semicontinuous system produces sludges having relatively better dewaterability and higher supernatant quality compared with the batch system. The latter system, however, can achieve a higher degree of volatile solids destruction and more significant decrease in oxygen uptake rate. A key factor is the shorter feed-starvation cycles and the hydraulic characteristics that allow frequent discharge of the products of endogenous metabolism in the semicontinuous system. It is important that caution should be applied on use of data obtained from batch aerobic digestion tests in the design of full scale aerobic digesters (which usually operate as semicontinuous systems).

Based on the results of this study, it appears that at $20^{o}C$ and loadings of 0.06 lb VSS/day/cu ft of digester capacity (0.96 kg VSS/day/ m^3), detention periods of 10 to 15 days are adequate for obtaining satisfactory stabilized sludge in the case of waste activated sludges precipitated with alum or ferric chloride. Detention periods of at least 15 days are required for the digestion of primary sludges precipitated with lime, especially when lime dosages in excess of 200 mg/l are used.

In an attempt to widen the applicability of the results of the study, the data were analyzed similarly to the procedure followed by

Cohen and Puntenney (1973), relating the percent reduction in volatile suspended solids to the product of temperature and sludge retention time. The SRT was between 0-21 days and the temperature was 20°C. The analysis was performed on data obtained for the waste activated sludges studied in Phase I and the estimation of percent VSS digested was based on mass balance of solids in the digester. This was necessary to compare, on a similar basis, the results of this study with the Denver full scale results on aerobic digestion of waste activated sludge reported by Cohen and Puntenney. Figure 44 shows that the data points from Phase I of this study follow the curve obtained by Cohen and Puntenney. However, the data on primary sludges (Phase II of the study) do not follow this curve. It suggests that the curve is not applicable for different types of sludge.

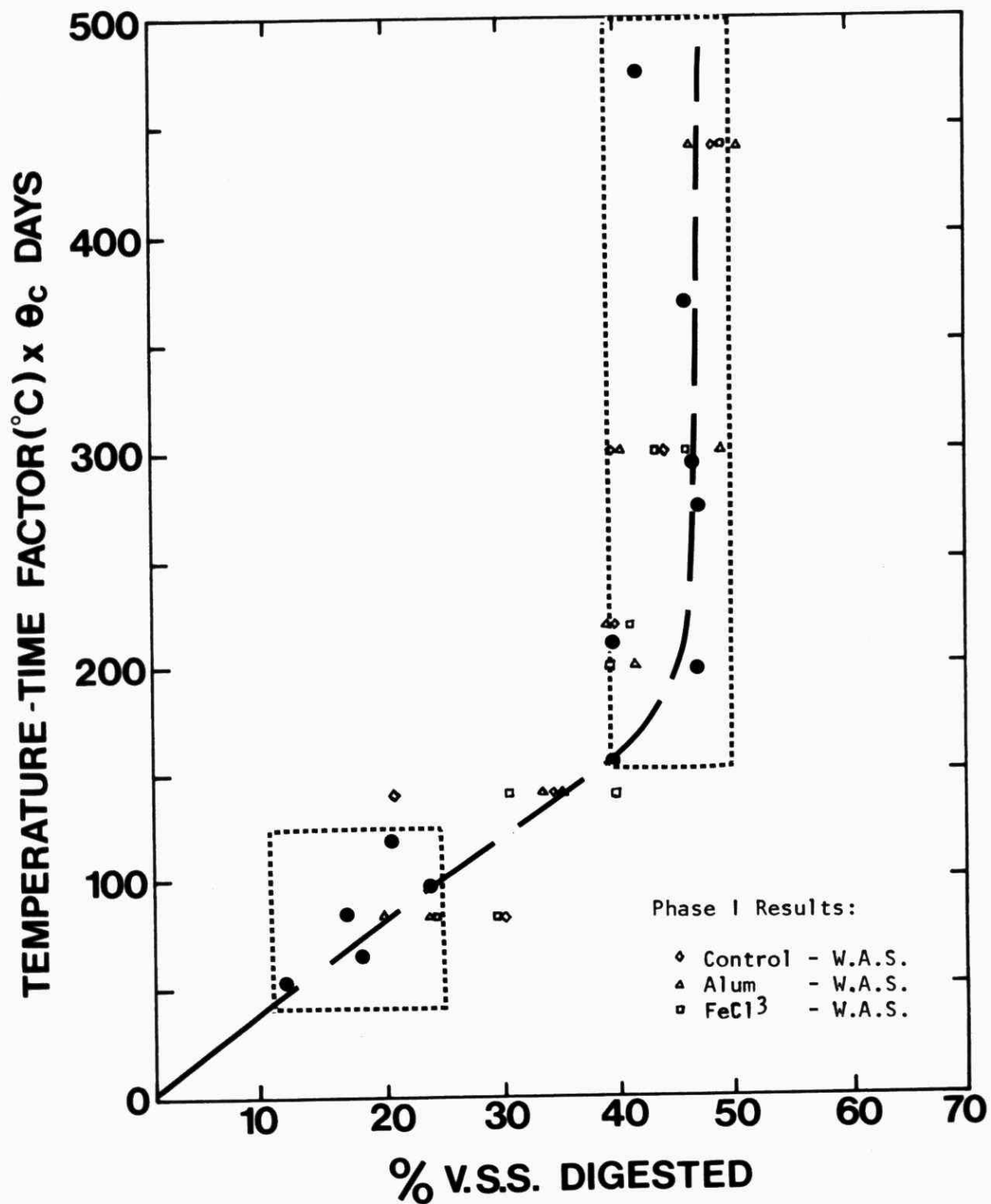These data are not shown in Figure 44 for the sake of simplicity.

FIGURE 44. TEMPERATURE - TIME FACTOR VS % VSS DIGESTED

(Cohen & Puntenney, 1973)

ACKNOWLEDGEMENTS

REFERENCES

Albertson, O., and R. Sherwood, (1969), "Phosphate Extraction Process",
Jour. Water Poll. Contr. Fed., 41, 1467-1490.

APHA (1971), Standard Methods for the Examination of Water and Wastewater ,
(American Public Health Association), Washington, D.C., 13th Ed.

Black, S.A., and Lewandowski, (1969), "Phosphorus Removal by Lime
Addition to a Conventional Activated Sludge Plant", Research Publ.
No. 36, Ontario Water Resources Comm., Toronto.

Buzzel, J.C., and C.N. Sawyer, (1967), "Removal of Algae Nutrients from
Raw Wastewater with Lime", Jour. Water Poll. Contr. Fed., 39,
R16-R24.

Cohen, D.B., and J.L. Puntenney, (1973), "Metro Denver's Experience with
Large Scale Aerobic Digestion of Waste Activated Sludge", Paper
presented at the 46th Annual Conference, Water Poll. Contr. Fed.,
Cleveland, Ohio.

Culp, R., and G. Culp, (1971), Advanced Wastewater Treatment , Van
Nostram Reinhold Co., New York.

Eckenfelder, W.W., and D.L. Ford, (1970), Water Pollution Control, The
Pemberton Press, Austin, Texas.

Ganczarczyk, J., and M.F. Hamoda, (1973), "Aerobic Digestion of Organic
Sludges Containing Inorganic Phosphorus Precipitates", Volume I,
Project No. 72-5-4, Research Report No. 3, Canada-Ontario Agreement
on Great Lakes Water Quality, Fisheries and Environment Canada and
Ontario Ministry of the Environment.

Minton, G.R., and D.A. Carlson, (1973), "Primary Sludges Produced by
the Addition of Lime to Raw Waste Water", Water Research (Brit.),
7, 12, 1821-1847.

Schmid, L.A., and R.C. McKinney, (1969), "Phosphate Removal by a Lime-
Biological Scheme", Jour. Water Poll. Contr. Fed., 41, 1259-1276.

Spohr, H., and A. Talts, (1970), "Phosphate Removal by pH-Controlled Lime
Dosage", Publ. Wks., 101, 63-67.

WPCF, Manual of Practice No. 11 - Operation of Wastewater Treatment Plants,
     Water Poll. Contr. Fed., Washington, D.C.

Zuckerman, N.M. and A.H. Molof, (1970), "High Quality Reuse Water by
     Chemical-Physical Wastewater Treatment", Jour. Water Poll. Contr.
     Fed., 42, 437-456.